

# Ultra-low-noise transimpedance amplifier with a single HEMT in pre-amplifier for measuring shot noise in cryogenic STM

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## Abstract

In this work, a design of transimpedance amplifier (TIA) for cryogenic scanning tunneling microscope (CryoSTM) is proposed. TIA with the tip-sample component in CryoSTM is called as CryoSTM-TIA. With transimpedance gain of  $1\text{ G}\Omega$ , the bandwidth of the CryoSTM-TIA is larger than  $200\text{ kHz}$ . The distinctive feature of the proposed CryoSTM-TIA is that its pre-amplifier is made of a single cryogenic high electron mobility transistor (HEMT), so the apparatus equivalent input noise current power spectral density at  $100\text{ kHz}$  is lower than  $6\text{ (fA)}^2/\text{Hz}$ . In addition, “bias-cooling method” can be used to in-situ control the density of the frozen  $\text{DX}^-$  centers in the HEMT doping area, changing its structure to reduce the device noises. With this apparatus, fast scanning tunneling spectra measurements with high-energy-resolution are capable to be performed. And, it is capable to measure scanning tunneling shot noise spectra (STSNS) at the atomic scale for various quantum systems, even if the shot noise is very low. It provides a powerful tool to investigate novel quantum states by measuring STSNS, such as detecting the existence of Majorana bound states in the topological quantum systems.

## 1 Introduction

High performance transimpedance amplifier (TIA) for cryogenic scanning tunneling microscope (CryoSTM) is a key element [1, 2]. In Ref.[3], it was proposed a design of TIA for CryoSTM. TIA with the tip-sample component in CryoSTM is called as CryoSTM-TIA. In that design, the CryoSTM-TIA has a transimpedance gain of  $1\text{ G}\Omega$ , a bandwidth of more than  $300\text{ kHz}$ , and its equivalent input noise current power spectral density (PSD) that characterizes the circuit inherent noise is  $21\text{ (fA)}^2/\text{Hz}$  at  $100\text{ kHz}$ . The CryoSTM-TIA is capable of measuring the scanning tunneling shot noise spectra (STSNS) of various quantum systems at atomic resolution, even if the measured noise current PSD is as small as a few  $\text{(fA)}^2/\text{Hz}$ . In Ref.[3], it was illustrated how the CryoSTM-TIA is used to measure STSNS of quantum systems to investigate novel quantum states, such as detecting

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Majorana bound states (MBSs) in iron-based superconductors [4]. In the CryoSTM-TIA, cascade the pre-amplifier (Pre-Amp) and the post-amplifier (Post-Amp) to form an operational amplifier (OPA) denoted as Macro-OPA. Pre-Amp in Macro-OPA is a differential amplifier made of a pair of high electron mobility transistors (HEMTs), where the HEMT is a kind of cryogenic GaAs MESFET [5, 6]. However, it is quite difficult to select cryogenic GaAs MESFETs with identical performances for pairing [2].

In this work, a design for the CryoSTM-TIA with a single HEMT in Pre-Amp is proposed. In the CryoSTM-TIA, cascade Pre-Amp and Post-Amp to form an inverting-amplifier (Inv-Amp), which is not OPA. The CryoSTM-TIA still has transimpedance gain of  $1\text{G}\Omega$  and bandwidth more than 200 kHz. However, its equivalent input noise current PSD is only  $5.3\text{ (fA)}^2/\text{Hz}$  at 100 kHz, i.e. 1/4 of that in Ref.[3], since a noisy HEMT is reduced. Therefore, the lower tunneling shot noise of quantum systems can be measured at the atomic scale with this apparatus. Furthermore, only a single HEMT is used in Pre-Amp, avoiding the difficulty of matching two identical HEMTs. And, “bias-cooling method” [5] can be used to in-situ reduce the inherent noise of the HEMT. With these advantages, this apparatus will be a powerful tool to investigate novel quantum states in various quantum systems, in the wider range of applications than that in Ref.[3], such as high- $T_c$  superconductors [7, 8], topological superconductors [4], MBSs [4, 9, 10, 11, 12], Andreev reflection [13, 14], and Kondo effect [15], etc.

## 2 Circuit of the proposed CryoSTM-TIA

The circuit of the proposed CryoSTM-TIA is shown in Fig.1. It consists of several components: the single HEMT amplifier part of Pre-Amp shown in the dashed box (a1) of Fig.1, the power supply of Pre-Amp in the dashed box (a2), Post-Amp shown in the dashed box (b), the compensated feedback network shown in the dashed box (c), and the signal source circuit shown in the dashed box (d). The two stage amplifier made of Pre-Amp and Post-Amp is called as Inv-Amp. Inv-Amp is connected with the feedback network to form TIA. The input G of TIA is connected to the signal source circuit, to form the CryoSTM-TIA. The components placed in the cryogenic zone are shown in the dotted box. The parameters of all components of the CryoSTM-TIA circuit are listed in Table 1.

### 2.1 Design of Pre-Amp

As shown in Fig.1, only a single cryogenic HEMT is used in Pre-Amp. The HEMT in this work is CNRS-HEMT (denoted as HEMT) [5, 6] developed by CNRS/LPN in France with the excellent cryogenic and noise characteristics. It is capable of operating under 0.5 K with only 0.1 mW on the ideal operating point of “ $V_{ds} = 100\text{ mV}$  and  $I_{ds} = 1\text{ mA}$ ”. Its parameters are listed in Table 1, where  $e_H^2$  is its equivalent input noise voltage PSD and  $i_H^2$  is its equivalent input noise current PSD [6].

The single HEMT amplifier part of Pre-Amp is shown in dashed box (a1) in Fig.1. The source of HEMT is grounded through a resistor  $R_s$  and a small variable resistor  $R_{s1}$ .  $R_S = R_s + R_{s1}$ , and a capacitor  $C_S$  of  $11\text{ }\mu\text{F}$  is in parallel with  $R_S$ . Drain  $O_1$  of HEMT is connected to the load resistor  $R_1$ . The resistor  $R_h$  is grounded through the variable resistor  $R_{h1}$ .  $R_H = R_h + R_{h1}$ . The other end of  $R_h$ , denoted as  $O_2$ , is connected to the resistor  $R_2$ , and L as the other end of  $R_2$  is connected to P (the other end of  $R_1$ ) through

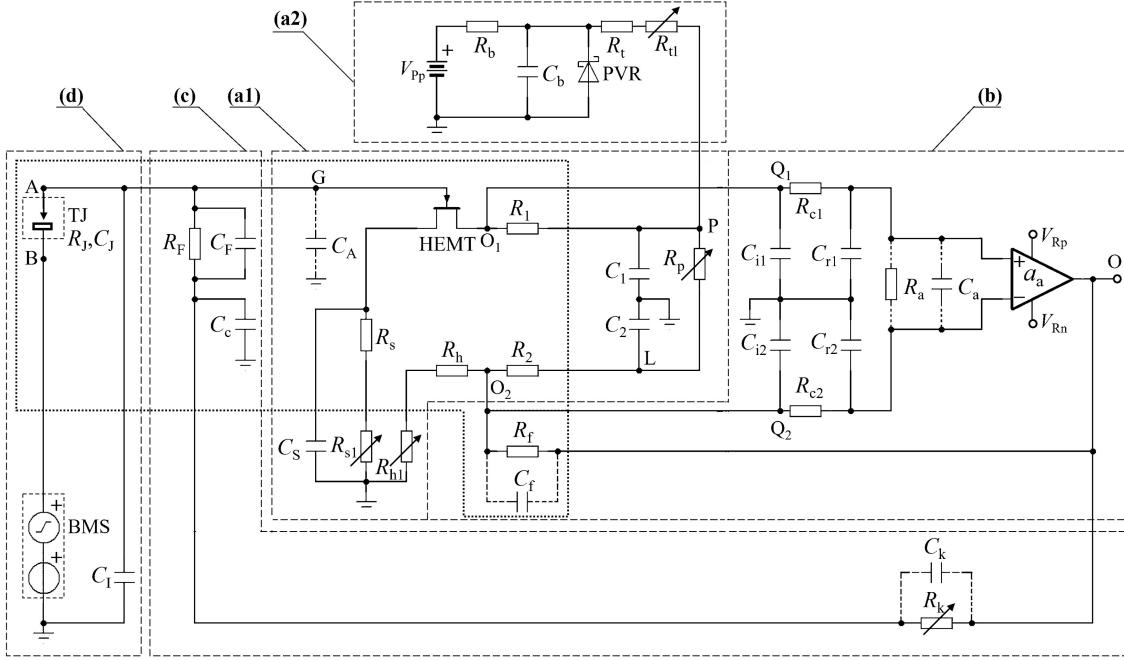


Figure 1: Circuit of the proposed CryoSTM-TIA. Single HEMT amplifier part of Pre-Amp is shown in the dashed box (a1), the power supply of Pre-Amp in the dashed box (a2), Post-Amp in the dashed box (b), the compensated feedback network in the dashed box (c), and the signal source circuit in the dashed box (d). The components placed in the cryogenic zone are shown in the dotted box. The parameters of all components of CryoSTM-TIA circuit are listed in Table 1.

a small variable resistor  $R_p$ .  $R_1 = R_2 = R_L$ . P is connected to the power supply of Pre-Amp. P and L are grounded through the large capacitors  $C_1$  and  $C_2$  respectively. In the power supply,  $R_T = R_t + R_{t1}$ , and  $R_{t1}$  is a variable resistor.  $C_A$  is the input capacitance of Pre-Amp. HEMT,  $R_s$ ,  $R_h$ ,  $R_1$ , and  $R_2$  are placed in the cryogenic zone, shown in the dotted box.  $C_1$  is the capacitance of the cable that connects Gate G of HEMT and the tip in the CryoSTM. HEMT is as close to the tip as possible to reduce  $C_1$ , which can be less than 0.5 pF [16]. The operating point adjustment for Pre-Amp is shown in Sect.4. The Pre-Amp parameters are shown in Table 1.

For Pre-Amp, as AC voltage  $\dot{V}$  is applied to input G, the AC voltage difference between  $O_1$  and  $O_2$  is denoted as  $\dot{V}_{op}$ .  $A_{vP} = \dot{V}_{op}/\dot{V}$  is the voltage gain of Pre-Amp. Since the transit frequency for the CNRS-HEMT is  $g_m/(2\pi C_{gs}) \approx 1$  GHz, the bandwidth of Pre-Amp is more than 30 MHz. In  $\max\{g_m/(2\pi C_s), 1/(2\pi R_s C_s)\} \ll f \leq 3$  MHz (i.e.  $30 \text{ Hz} \ll f \leq 3 \text{ MHz}$  with the parameters listed in Table 1),

$$A_{vP} \approx -g_m R_d, \quad (2.1)$$

where  $R_d = R_L/(1 + g_d R_L)$ . i.e.,  $A_{vP} \approx -20$  in  $30 \text{ Hz} \ll f \leq 3 \text{ MHz}$ . The input capacitance of Pre-Amp is

$$C_A = C_{gs} + (1 - A_{vP})C_{gd}. \quad (2.2)$$

Table 1: Parameters of all components of CryoSTM-TIA circuit

HEMT (CNRS-HEMT)			
Gate-source resistance $R_A$			$>10$ T $\Omega$
Transconductance $g_m$			40 mS
Channel conductance $g_d$			1 mS
Gate-source capacitance $C_{gs}$			5 pF
Gate-drain capacitance $C_{gd}$			1 pF
Drain-source voltage $V_{ds}$			100 mV
Drain-source current $I_{ds}$			1 mA
Equivalent input noise voltage PSD $\overline{e_H^2}$	10 kHz		$0.25 \text{ (nV)}^2/\text{Hz}$
	100 kHz		$0.07 \text{ (nV)}^2/\text{Hz}$
Equivalent input noise current PSD $\overline{i_H^2}$	10 kHz		$0.1 \text{ (fA)}^2/\text{Hz}$
	100 kHz		$1 \text{ (fA)}^2/\text{Hz}$
Pre-Amp			
$R_s + R_{s1}$	$50 \pm 5 \text{ } \Omega$	$C_S$	11 $\mu\text{F}$
$R_h + R_{h1}$	$150 \pm 5 \text{ } \Omega$	$R_1, R_2$	1 k $\Omega$
$R_p$	$5 \pm 5 \text{ } \Omega$		
$C_1$	22 $\mu\text{F}$	$C_2$	11 $\mu\text{F}$
PVR	LM4050-10	$R_b$	2 k $\Omega$
$R_t + R_{t1}$	$4400 \pm 10 \text{ } \Omega$	$V_{Pp}$	+15 V
THS4021 as Rear-OPA			
$a_{a0}$	94 dB	$f_b$	16 kHz
$C_a$	1.5 pF	$R_a$	1 M $\Omega$
$V_{Rp}$	+15 V	$V_{Rn}$	-15 V
Equivalent input noise voltage PSD $\overline{e_a^2}$	2.25 (nV) <sup>2</sup> /Hz in $f > 10$ kHz		
Equivalent input noise current PSD $\overline{i_a^2}$	4 (pA) <sup>2</sup> /Hz in $f > 10$ kHz		
Post-Amp			
$R_f$	200 k $\Omega$	$C_{i1}, C_{i2}$	150 pF
$R_{c1}, R_{c2}$	100 $\Omega$	$C_{r1}, C_{r2}$	50 pF
Feedback network			
$R_F$	1 G $\Omega$	$C_F$	$\sim 3$ pF
$R_k$	300 k $\Omega$	$C_k$	$\sim 0.2$ pF
$C_c$	10 nF		
Signal source circuit			
$R_J$	$\geq 1$ M $\Omega$	$C_I$	$\sim 0.5$ pF

Note:  $\pm$  indicates the variable resistance range. Without specification, the default value after  $\pm$  is 0.

i.e.,  $C_A \approx 26$  pF in  $30 \text{ Hz} \ll f \leq 3 \text{ MHz}$ . The input resistance of Pre-Amp  $R_A$  is the gate-source resistance of HEMT, and  $R_A > 10 \text{ T}\Omega$ , so it can be considered as infinity.

The power supply of Pre-Amp is shown in the dashed box (a2) in Fig.1. A precision voltage reference (PVR) LM4050-10 [17] is used in the power supply to provide a constant voltage of 10 V with the typical temperature coefficient of  $\pm 40$  ppm/ $^\circ\text{C}$ . The noises from PVR are eliminated by  $C_1$ ,  $C_2$ , and  $R_T$ .

For a differential amplifier, there is a feedback between the two branches of the transistors, so the high common mode rejection ratio (CMRR) can be realized for the differential amplifier. For the differential amplifier as Pre-Amp in Ref.[3], if a resistor is instead of HEMT (H2) with the same DC resistance, Inv-Amp may become a non-inverting amplifier as  $f \rightarrow 0$ . For the design of Pre-Amp in this work, there is no feedback between the HEMT branch and  $R_H$  branch, therefore Inv-Amp in this work is always an inverting amplifier.

## 2.2 Design of Post-Amp and composition of Inv-Amp

In Fig.1, the Post-Amp circuit in the dashed box (b) is the same in structure as that in Ref.[3]. There is a commercial operational amplifier (OPA) in the circuit, called as Rear-OPA, which is the OPA with high gain-bandwidth-product, such as THS4021, OPA657, and LMH6624, etc. The Rear-OPA in this work is THS4021 [18]. The Post-Amp parameters are listed in Table 1.  $R_a$  and  $C_a$  are the input resistance and capacitance of Rear-OPA respectively.  $R_f$  of 200 k $\Omega$  is the feedback resistor, and it is placed in the cryogenic zone. Post-Amp also contains two cables that connect  $Q_1$  and  $Q_2$  in room temperature zone to outputs  $O_1$  and  $O_2$  of Pre-Amp in cryogenic zone respectively. The capacitance of the two cables is  $C_{i1}$  and  $C_{i2}$  respectively, and they may vary from 50 pF to 150 pF. In this work,  $C_{i1} = C_{i2} = C_i = 150$  pF is assumed.

A 1 meter cable with characteristic impedance of 50  $\Omega$  has a distributed capacitance of 100 pF and a distributed inductance of 250 nH, and its distributed LC structure results in several resonant gain peaks in [50 MHz, 1 GHz] [19]. Cascade Pre-Amp and Post-Amp to form Inv-Amp. In Inv-Amp, Post-Amp and Pre-Amp are connected by the cables (Cable  $O_1Q_1$  and Cable  $O_2Q_2$ ), and the resonant gain peaks may cause the self-oscillations, as some unexpected electromagnetic couplings may exist among the outputs and the inputs of the amplifiers. Two low-pass filters ( $R_{c1} = R_{c2} = R_c = 100$   $\Omega$  and  $C_{r1} = C_{r2} = C_r = 50$  pF) with the upper cut-off frequency of 30 MHz are added at the Rear-OPA inputs, these resonant gain peaks can be greatly reduced, thus avoiding the self-oscillations.

For the AC signal, the voltage gain of Inv-Amp is  $a_A = a_A(f)$ .  $a_A(f)$  can be expressed as

$$a_A = A_{vP}A_{vR}. \quad (2.3)$$

By the nodal analysis method,  $a_A$  can be obtained. And then, with  $A_{vP}$  expressed by Eq.(2.1),  $A_{vR}$  can be obtained by Eq.(2.3). In  $\max\{g_m/(2\pi C_S), 1/(2\pi R_S C_S)\} \ll f \leq 3$  MHz (i.e. 30 Hz  $\ll f \leq 3$  MHz with the parameters listed in Table 1),

$$A_{vR} \approx \frac{R_f}{R_{HL}} \cdot \frac{1 + j2\pi f R_{HL} C_{ir}}{1 + j2\pi f R_d C_{ir}} \cdot \frac{1}{1 + \frac{R_f}{a_a R_{HL}} + j2\pi f \frac{R_f C_{ir}}{a_a}}, \quad (2.4)$$

where  $R_{HL} = R_H R_L / (R_H + R_L)$ ,  $C_{ir} = C_i + C_r$ , and  $a_a$  is the voltage gain of the Rear-OPA. In this work,  $R_f \gg R_{HL}$  and  $R_a \gg R_{HL}$ . And,  $a_a$  can be approximately expressed as  $a_a = a_{a0}/(1 + jf/f_b)$  in (0, 40 MHz] for THS4021.

With the parameters in Table 1, the Inv-Amp performances are simulated by TINA-TI [20]. Fig.2 show the curves of  $|a_A(f)|_{dB}$  and  $\angle(a_A(f))$  simulated by TINA-TI. By the nodal analysis method,  $a_A(f)$  is calculated by the equations established with all components listed in Table 1 [21], which is also shown in Fig.2. The curves of  $|a_A(f)|_{dB}$  and  $\angle(a_A(f))$  calculated by the nodal analysis method are identical with the simulated ones respectively.  $|a_A(f)|_{dB}$  and  $\angle(a_A(f))$  are also calculated by Eqs.(2.1), (2.3), and (2.4), and the calculated curves in Fig.2 are almost identical with the simulated ones respectively in [3 kHz, 10 MHz], which verifies the correctness of Eqs.(2.1),(2.3), and (2.4).

## 2.3 Frequency compensation of feedback loop

In order to increase the bandwidth of the CryoSTM-TIA, for the high feedback resistor  $R_F$  with parasitic capacitance  $C_F$ , frequency compensation must be used in the feedback

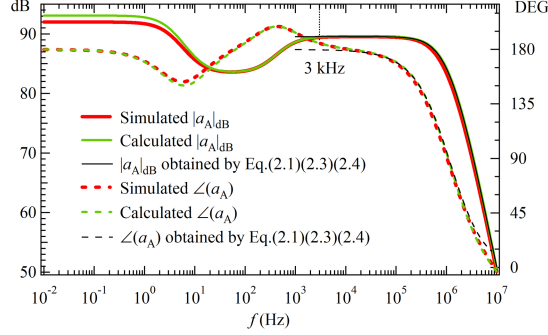


Figure 2: The Inv-Amp voltage gain  $a_A(f)$ . The solid curves are the curves of  $|a_A(f)|_{\text{dB}}$ , and the dashed curves are the curves of  $\angle(a_A(f))$ . The red curves are the TINA-TI simulation results, the green curves are the calculated results with the nodal analysis method, and the black curves are the calculated results obtained by Eqs.(2.1), (2.3), and (2.4).

loop [1, 22]. In Fig.1, the compensated feedback network is shown in the dashed box (c). Taking  $C_c$  equal to  $kC_F$ , where  $k$  is above  $10^3$ , adjust  $R_k$  equal to  $R_F/k$ , realizing  $R_k C_c = R_F C_F$ . The output voltage of TIA as  $\dot{V}_o$  generates the current  $\dot{I}_F$  flowing to input G of TIA, so

$$Z_F(f) = \frac{\dot{V}_o}{\dot{I}_F} \approx \frac{R_k + R_F}{1 + j2\pi f R_k C_k} \approx \frac{R_F}{1 + j2\pi f R_k C_k},$$

where  $C_k$  is the parasitic capacitance of  $R_k$  [1, 3, 22].  $Z_F(f)$  can be considered as the impedance of the feedback network. In Ref.[22], it has been achieved in experiments to broaden the bandwidth of the feedback network with the very high feedback resistor  $R_F$  of 10 G $\Omega$  to MHz. In (0, 1 MHz], with the parameters listed in Table 1,  $|Z_F(f)| \approx R_F/|1 + j2\pi f R_k C_k| > R_F/1.008$  and  $|\angle(Z_F(f))| \leq 31.5^\circ$ , so it can be considered that  $Z_F(f)$  is equal to  $R_F$ .

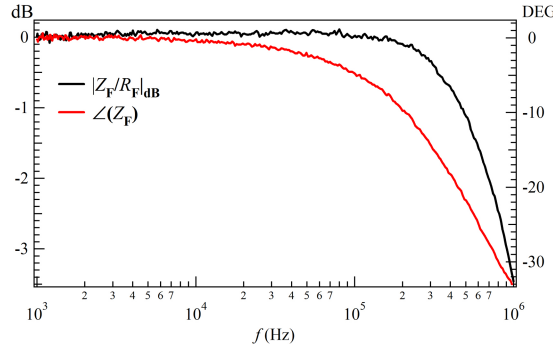


Figure 3: The experimental results for the frequency compensation. At 4.2 K,  $R_F$  is 1.16 G $\Omega$  and  $C_F$  is estimated as 3.36 pF. As  $R_k = 380$  k $\Omega$  and  $C_c = 10$  nF, the black curve shows that the bandwidth of  $|Z_F/R_F|_{\text{dB}}$  is broadened to 905 kHz, and the red curve shows  $\angle(Z_F)$  as the phase of  $Z_F$  is  $-31.5^\circ$  at 905 kHz.

In order to verify the above frequency compensation method, the following experiment

is done. A resistor with  $500 \text{ M}\Omega (\pm 25 \text{ ppm}/^\circ\text{C})$  at room temperature is chosen as  $R_F$ , which is  $1.16 \text{ G}\Omega$  at  $4.2 \text{ K}$ .  $R_k$  is a  $390 \text{ k}\Omega$  resistor in series with a  $0 \sim 20 \text{ k}\Omega$  potentiometer, and  $C_c$  is a COG ceramic capacitor of  $10 \text{ nF}$ . In order to easily adjust the frequency compensation, a  $3 \text{ pF}$  capacitor is paralleled with the  $R_F$ , so that the  $C_F$  is about  $3.36 \text{ pF}$ . Fig.3 shows the experimental results for the frequency compensation, in which  $|Z_F| = R_F/\sqrt{2}$  at  $905 \text{ kHz}$ , and  $\angle(Z_F)$  as the phase of  $Z_F$  is  $-31.5^\circ$  at  $905 \text{ kHz}$ .

## 2.4 Circuit stability of the proposed CryoSTM-TIA

In Fig.1, the signal source circuit is shown in the dashed box (d), and its parameters are shown in Table 1. The differential resistance of the tip-sample tunnel junction (TJ) is  $R_J$ , which is limited to no less than  $10^{-3}R_F$  in this design. The capacitance of TJ is  $C_J$ , which is in parallel with  $R_J$ . And,  $C_J$  is estimated as several fF [3].  $C = C_A + C_I + C_J$  in this work.  $C_J$  is at least two orders of magnitude less than  $C_A + C_I$ , so it can be ignored in  $C$  and  $C \approx C_A + C_I$ . The DC bias & modulated signal voltage source is denoted as BMS, which provides the DC bias  $V_i$  and AC sinusoidal modulated signal voltage  $\dot{V}_i$  for the CryoSTM-TIA. In the following simulation,  $C_I$  is always taken as  $0.5 \text{ pF}$  [16]. TIA connects the signal source circuit to form the CryoSTM-TIA. According to the parameters in Table 1, the performances of the CryoSTM-TIA can be simulated by TINA-TI.

The loop gain  $T_L$  of the proposed CryoSTM-TIA is [23]

$$T_L(f) = -a_A(f)\beta(f) = -a_A(f)/[1/\beta(f)],$$

in which  $\beta(f)$  is the feedback factor, and its reciprocal is,

$$1/\beta(f) \approx 1 + Z_F[1/R_J + 1/R_A + j2\pi f(C_A + C_I)]. \quad (2.5)$$

By Eq.(2.5),  $|1/\beta(f)|$  and  $\angle(1/\beta(f))$  can be calculated. Fig.4(a) shows the calculated results of  $|1/\beta(f)|_{\text{dB}}$  and  $\angle(1/\beta(f))$  with  $R_J = +\infty$ , and Fig.4(b) shows those with  $R_J = 1 \text{ M}\Omega$ .  $|a_A|_{\text{dB}}$  and  $\angle(a_A)$  are also shown in Fig.4. Both figures show  $|T_L|_{\text{dB}} = |a_A|_{\text{dB}} - |1/\beta(f)|_{\text{dB}} \leq -10 \text{ dB}$  in  $f \geq 465 \text{ kHz}$  and  $\angle(T_L) = \angle(-a_A) - \angle(1/\beta) = \angle(a_A) - 180^\circ - \angle(1/\beta) > -130^\circ$  in  $f \leq 465 \text{ kHz}$ . Therefore, the CryoSTM-TIA is stable with gain margin more than  $10 \text{ dB}$  and phase margin more than  $50^\circ$ .

## 2.5 Voltage gain and transimpedance gain of the proposed CryoSTM-TIA

With the compensated feedback network mentioned in Sect.2.3, it can be considered that  $Z_F$  is equal to  $R_F$  in  $(0, 1 \text{ MHz}]$ . Considering the TJ capacitance  $C_J$ , the TJ impedance should be  $Z_J = R_J/(1 + j2\pi f R_J C_J)$ . And,  $C \approx C_A + C_I$ . As the AC input voltage  $\dot{V}_i$  is applied by BMS, the output voltage of the CryoSTM-TIA is  $\dot{V}_o$ , and the voltage gain of the CryoSTM-TIA is  $A_v = \dot{V}_o/\dot{V}_i$ . In  $(0, 1 \text{ MHz}]$ , by the nodal analysis method,  $A_v$  is

$$A_v \approx -\frac{R_F}{Z_J} \cdot \frac{1}{1 - \frac{1}{a_A} - \frac{R_F}{a_A R_J} - \frac{R_F}{a_A R_A} - j2\pi f \frac{R_F(C_A + C_I)}{a_A}}. \quad (2.6)$$

Setting  $\dot{V}_i = 0$  and applying a sinusoidal current source  $\dot{I}_i$  in parallel with TJ, the output voltage  $\dot{V}_o$  is generated at the output of the CryoSTM-TIA.  $A_i = \dot{V}_o/\dot{I}_i$  is called

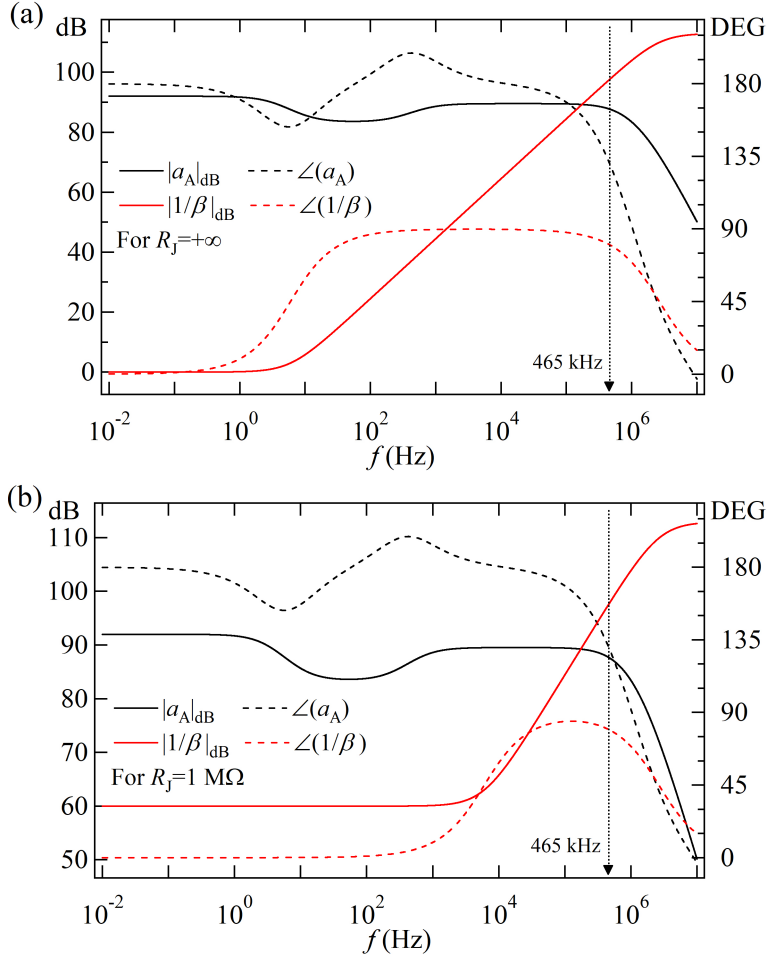


Figure 4: TINA-TI simulation results for the voltage gain Inv-Amp  $a_A$ , and  $1/\beta(f)$  (a) with  $R_J = +\infty$ , (b) with  $R_J = 1 \text{ M}\Omega$ . Both figures show  $|T_L|_{\text{dB}} = |a_A|_{\text{dB}} - |1/\beta(f)|_{\text{dB}} \leq -10 \text{ dB}$  in  $f \geq 465 \text{ kHz}$  and  $\angle(T_L) = \angle(-a_A) - \angle(1/\beta) = \angle(a_A) - 180^\circ - \angle(1/\beta) > -130^\circ$  in  $f < 465 \text{ kHz}$ . Hence, the CryoSTM-TIA is stable enough.

as the transimpedance gain of the CryoSTM-TIA. In  $(0, 1 \text{ MHz}]$ ,  $A_i$  is

$$A_i \approx -\frac{R_F}{1 - \frac{1}{a_A} - \frac{R_F}{a_A R_J} - \frac{R_F}{a_A R_A} - j2\pi f \frac{R_F(C_A + C_1)}{a_A}}. \quad (2.7)$$

Disconnecting TIA with the signal source circuit, and applying a sinusoidal current source  $\dot{I}_{iT}$  into the input of TIA, the output voltage  $\dot{V}_{oT}$  is generated at the output of TIA.  $A_{iT} = \dot{V}_{oT}/\dot{I}_{iT}$  is called as the transimpedance gain of TIA. In  $(0, 1 \text{ MHz}]$ ,  $A_{iT}$  is

$$A_{iT} \approx -\frac{R_F}{1 - \frac{1}{a_A} - \frac{R_F}{a_A R_A} - j2\pi f \frac{R_F C_A}{a_A}},$$

Considering  $R_A \gg R_F$  and  $|a_A| \gg 1$ ,  $A_{iT}$  is

$$A_{iT} \approx -\frac{R_F}{1 - j2\pi f \frac{R_F C_A}{a_A}}, \quad (2.8)$$



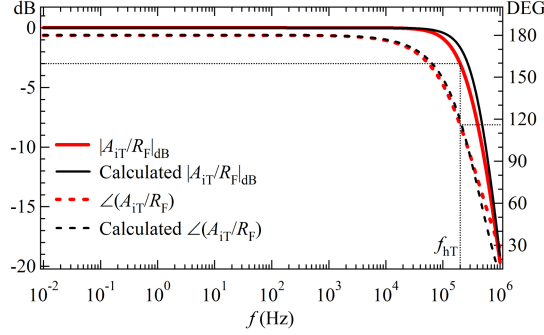


Figure 5: TINA-TI simulation results for  $A_{iT}/R_F$ ,  $A_{iT}$  is the transimpedance gain of TIA in the proposed CryoSTM-TIA.  $|A_{iT}(f_{hT})/R_F|_{dB} = -3$  dB and  $\angle(A_{iT}(f_{hT})/R_F) = 116^\circ$  at  $f_{hT}$  about 201 kHz.

In Fig.5,  $|A_{iT}/R_F|_{dB}$  and  $\angle(A_{iT}/R_F)$  calculated by Eq.(2.8) with the parameters in Table 1 is consistent with their TINA-TI simulation results in [10 mHz, 1 MHz], which verifies the correctness of Eq.(2.8) for  $A_{iT}$ . The upper cut-off frequency of  $A_{iT}(f)/R_F$ , i.e. its  $-3$  dB frequency  $f_{hT}$  is about 201 kHz. Comparing Eq.(2.7) with Eq.(2.8), as  $C_A + C_I + C_J \approx C_A + C_I \approx C_A$  and  $R_J \geq 10^{-3}R_F$ , the upper cut-off frequency of the CryoSTM-TIA is approximately equal to  $f_{hT}$ .

## 2.6 Transient response of the proposed CryoSTM-TIA

The simulation results for the transient response of the proposed CryoSTM-TIA are shown in Supplemental file 3 [24]. For the CryoSTM-TIA, the time taken from adding the input step signal voltage to the output response stably within a certain error is called transient response time  $t_r$ . For the simulations, a resistor with a constant resistance  $R_0$  is instead of the tip-sample junction. As  $R_0 \geq 30$  M $\Omega$ , for 0.1% error,  $t_r < 5$   $\mu$ s. As  $5$  M $\Omega \leq R_0 < 30$  M $\Omega$ , for 1% error,  $t_r < 5$   $\mu$ s. As  $1$  M $\Omega \leq R_0 < 5$  M $\Omega$ , for 3% error,  $t_r < 5$   $\mu$ s.

## 3 Inherent noise of the proposed CryoSTM-TIA

For the circuit of the proposed CryoSTM-TIA shown in Fig.1, the differential equivalent circuit with all noise sources is used to calculate its equivalent input noise. The details for the noise calculations are shown in Supplemental file 4 [25].

### 3.1 Equivalent input voltage noise and equivalent input current noise of Inv-Amp

The equivalent input noise voltage and equivalent input noise current of HEMT are denoted as  $e_H$  and  $i_H$  respectively. The resistors  $R_1$ ,  $R_2$ , and  $R_f$  are in the cryogenic zone of 4.2 K, and their noises in  $f > 1$  kHz are thermal noise, which can be neglected [3].  $R_h$  is in the cryogenic zone of 4.2 K, and the thermal noise voltage of the resistor  $R_H$  is  $e_{RH}$ . The thermal noise voltage of the resistor  $R_{c1}$  is  $e_1$ , and that of  $R_{c2}$  is  $e_2$ . The equivalent input noise voltage and equivalent input noise current of the Rear-OPA are denoted as  $e_a$  and  $i_a$  respectively. These noise sources are independent. The equivalent

input noise voltage and equivalent input noise current of Inv-Amp are denoted as  $e_A$  and  $i_A$  respectively.  $\overline{e_A^2}$  is the equivalent input noise voltage PSD of Inv-Amp,  $\overline{i_A^2}$  is its equivalent input noise current PSD,  $\overline{e_A i_A^*}$  is its equivalent input noise voltage-current PSD, and  $\overline{i_A e_A^*}$  is its equivalent input noise current-voltage PSD. By the nodal analysis method and Wiener-Sinichin theorem, ignoring the minor terms, it is obtained that [25]

$$\overline{e_A^2} = \overline{e_H^2} + \frac{R_{HL}^2}{R_H^2} \frac{\overline{e_{RH}^2}}{A_{VP}^2} + \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{VP}^2} + \left(1 + \frac{R_{HL}}{R_d}\right)^2 \frac{\overline{i_a^2}}{g_m^2}, \quad (3.1)$$

$$\begin{aligned} \overline{i_A^2} = \overline{i_H^2} + (2\pi f)^2 \frac{C_A^2}{A_{VP}^2} & \left( \frac{R_{HL}^2}{R_H^2} \overline{e_{RH}^2} + \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) \\ & + (2\pi f)^2 \left( C_{gs} + C_{gd} + \frac{R_{HL}}{R_d} C_A \right)^2 \frac{\overline{i_a^2}}{g_m^2}, \end{aligned} \quad (3.2)$$

$$\begin{aligned} \overline{e_A i_A^*} = (\overline{i_A e_A^*})^* = -j2\pi f \frac{C_A}{A_{VP}^2} & \left( \frac{R_{HL}^2}{R_H^2} \overline{e_{RH}^2} + \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) \\ & - j2\pi f \left( C_{gs} + C_{gd} + \frac{R_{HL}}{R_d} C_A \right) \left( 1 + \frac{R_{HL}}{R_d} \right) \frac{\overline{i_a^2}}{g_m^2}. \end{aligned} \quad (3.3)$$

According to the parameters listed in Table 1, for Inv-Amp in this work,  $\overline{e_A^2} = 0.28$  (nV)<sup>2</sup>/Hz and  $\overline{i_A^2} = 0.14$  (fA)<sup>2</sup>/Hz at  $f = 10$  kHz, and  $\overline{e_A^2} = 0.09$  (nV)<sup>2</sup>/Hz and  $\overline{i_A^2} = 4.9$  (fA)<sup>2</sup>/Hz at  $f = 100$  kHz. For the Macro-OPA in Ref.[3],  $\overline{e_A^2} = 0.5$  (nV)<sup>2</sup>/Hz and  $\overline{i_A^2} = 0.8$  (fA)<sup>2</sup>/Hz at  $f = 10$  kHz, and  $\overline{e_A^2} = 0.14$  (nV)<sup>2</sup>/Hz and  $\overline{i_A^2} = 20$  (fA)<sup>2</sup>/Hz at  $f = 100$  kHz. The resistor  $R_H$  in Inv-Amp in this work replaces the transistor H2 in the Macro-OPA in Ref.[3]. The noise generated by  $R_H$  is 2 orders of magnitude smaller than that generated by H2 in the Macro-OPA in Ref.[3], i.e.  $\overline{e_{RH}^2} \ll A_{VP}^2 \overline{e_H^2}$ . Therefore, the equivalent input noises of Inv-Amp in this work are much lower than those of the Macro-OPA in Ref.[3].

In Eqs.(3.1), (3.2), and (3.3),  $\overline{e_{RH}^2} R_{HL}^2 / R_H^2$  is one order of magnitude smaller than  $\overline{e_a^2}$ . In Eq.(3.1),  $(1 + R_{HL}/R_d)^2 \overline{i_a^2} / g_m^2$  is 2 orders of magnitude smaller than  $\overline{e_H^2}$ . In Eq.(3.2),  $(C_{gs} + C_{gd} + C_A R_{HL}/R_d)^2 \overline{i_a^2} / g_m^2$  is one order of magnitude smaller than  $C_A^2 \overline{e_a^2} / A_{VP}^2$ . In Eq.(3.3),  $(C_{gs} + C_{gd} + C_A R_{HL}/R_d) (1 + R_{HL}/R_d) \overline{i_a^2} / g_m^2$  is one order of magnitude smaller than  $C_A \overline{e_a^2} / A_{VP}^2$ . Further ignoring the minor terms in Eqs.(3.1), (3.2), and (3.3),

$$\overline{e_A^2} \approx \overline{e_H^2} + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{VP}^2, \quad (3.4)$$

$$\overline{i_A^2} \approx \overline{i_H^2} + (2\pi f)^2 C_A^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{VP}^2, \quad (3.5)$$

$$\overline{e_A i_A^*} \approx (\overline{i_A e_A^*})^* = -j2\pi f C_A (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{VP}^2. \quad (3.6)$$

### 3.2 Equivalent input voltage noise and equivalent input current noise of the proposed TIA

The equivalent input noise voltage PSD of TIA is denoted as  $\overline{e_T^2}$ , its equivalent input noise current PSD is  $\overline{i_T^2}$ , its equivalent input noise voltage-current PSD is  $\overline{e_T i_T^*}$ , and its equivalent input noise current-voltage PSD is  $\overline{i_T e_T^*}$ . They are [25]

$$\overline{e_T^2} = \overline{e_A^2} \approx \overline{e_H^2} + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2, \quad (3.7)$$

$$\begin{aligned} \overline{i_T^2} &= 4k_B T/R_F + \overline{e_A^2}/R_F^2 + \overline{i_A^2} \\ &\approx 4k_B T/R_F + \overline{e_H^2}/R_F^2 + \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{vP}^2 R_F^2} \\ &\quad + \overline{i_H^2} + (2\pi f)^2 C_A^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2, \end{aligned} \quad (3.8)$$

$$\begin{aligned} \overline{e_T i_T^*} &= (\overline{i_T e_T^*})^* = \overline{e_A^2}/R_F + \overline{e_A i_A^*} \\ &\approx \overline{e_H^2}/R_F + \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{vP}^2 R_F} \\ &\quad - j2\pi f C_A (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2. \end{aligned} \quad (3.9)$$

### 3.3 Equivalent input current noise of the proposed CryoSTM-TIA

The equivalent input noise current PSD of the proposed CryoSTM-TIA is [25]

$$\begin{aligned} \overline{i_{in}^2} &= \overline{i_T^2} + [1/R_J^2 + (2\pi f)^2 C_{IJ}^2] \overline{e_T^2} \\ &\quad + (1/R_J + j2\pi f C_{IJ}) \overline{e_T i_T^*} + (1/R_J - j2\pi f C_{IJ}) \overline{i_T e_T^*}, \end{aligned} \quad (3.10)$$

where  $C_{IJ} = C_I + C_J$ . Putting Eqs.(3.7), (3.8), and (3.9) into Eq.(3.10),

$$\begin{aligned} \overline{i_{in}^2} &= \overline{i_H^2} + 4k_B T/R_F + (1/R_J + 1/R_F)^2 [\overline{e_H^2} + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2] \\ &\quad + (2\pi f)^2 [C_{IJ}^2 \overline{e_H^2} + C^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2], \end{aligned} \quad (3.11)$$

i.e.

$$\overline{i_{in}^2} = \overline{i_A^2} + 4k_B T/R_F + (1/R_J + 1/R_F)^2 \overline{e_A^2} + \overline{i_{CIJ}^2}, \quad (3.12)$$

where  $\overline{i_{CIJ}^2} = (2\pi f)^2 [C_{IJ}^2 \overline{e_A^2} + 2C_A C_{IJ} (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2})/A_{vP}^2]$ .

For the proposed CryoSTM-TIA,  $R_F = 1 \text{ G}\Omega$ ,  $C_A = 26 \text{ pF}$ ,  $C_I = 0.5 \text{ pF}$ , and  $C_J = 10 \text{ fF}$ .  $R_F$  and  $TJ$  are in the cryogenic zone at 4.2 K. As  $R_J = 1 \text{ M}\Omega$ ,  $\overline{i_{in}^2}$  and its four components are listed in Table 2. The noise components of the CryoSTM-TIA in Ref.[3] are also shown in Table 2. The CryoSTM-TIA proposed in this work has an equivalent input noise current PSD of  $0.62 \text{ (fA)}^2/\text{Hz}$  at 10 kHz and  $5.3 \text{ (fA)}^2/\text{Hz}$  at 100 kHz, which are much lower than those in Ref.[3].

For the Epi-wafer of the CNRS-HEMT, as Si is doped in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , each dopant gives rise to two types of electronic states: a shallow and delocalized donor level associated

Table 2: Noise components of CryoSTM-TIAs

Pre-Amp type	Single HEMT Amp		Pre-Amp in Ref.[3]	
$f$ (kHz)	10	100	10	100
$e_A^2 ((\text{nV})^2/\text{Hz})$	0.28	0.09	0.5	0.14
Unit for the following terms is $(\text{fA})^2/\text{Hz}$				
$\overline{i_A^2}$	0.14	4.9	0.8	20
$4k_B T/R_F$	0.2	0.2	0.2	0.2
$\overline{i_{CIJ}^2}$	0.0033	0.15	0.03	0.7
$(\frac{1}{R_I} + \frac{1}{R_F})^2 \overline{e_A^2}$	0.28	0.09	0.5	0.14
$i_{\text{in}}^2$ as total	0.62	5.3	1.5	21

with the normal substitutional site configuration, called as shallow donor state; and a more localized acceptor level, known as  $\text{DX}^-$  center, arising from a lattice distortion. In  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , as  $x > 0.22$ ,  $\text{DX}^-$  as a bound state is more stable than the shallow donor state. And,  $x = 0.37$  for CNRS-HEMT in this work. There is a large repulsion barrier  $E_{\text{cap}}$  in the transition from the shallow donor to  $\text{DX}^-$ , so  $\text{DX}^-$  is frozen as  $T < 120$  K [26, 27]. According to the work on the noise mechanism of the CNRS-HEMT [5], “bias-cooling method” can be used to control the density of the frozen  $\text{DX}^-$  centers in the doping area in the HEMT. This unique method, by which the in-situ modification of the HEMT structure is realized, can be used to reduce the noise generated by the HEMT. By cooling the HEMT with the positive gate-source voltage, more electrons in the HEMT are frozen into the  $\text{DX}^-$  centers. At low temperatures, the absolute value of the gate-source voltage required to maintain the HEMT at the ideal operating point is reduced, so that the gate leakage current is reduced, and thus the low frequency noises generated by the gate leakage current is reduced [5]. By the means, the inherent noise of the CryoSTM-TIA can be reduced. Moreover, if the HEMT used for the CryoSTM-TIA is not CNRS-HEMT, or its noise performances are not as good as those listed in Table 1, it can be remedied by “bias-cooling method”. This approach is very convenient for cases with only a single HEMT in Pre-Amp.

## 4 Operating state adjustment and DC tunneling current measurements

For the CryoSTM-TIA in Fig.1, along with the circuit parameters listed in Table 1, its operating state can be adjusted as follows. (1) Disconnect Pre-Amp from Post-Amp and ground the input of Pre-Amp (i.e. the Gate G of HEMT). Keep  $R_p$  to 0. Adjust  $R_{s1}$ ,  $R_{h1}$ , and  $R_{t1}$  to achieve HEMT at the ideal operating point ( $V_{\text{ds}} = 100$  mV,  $I_{\text{ds}} = 1$  mA) and the potentials at  $\text{O}_1$  and  $\text{O}_2$  equal. That is to say,  $R_{s1}$  and  $R_{h1}$  are adjusted to realize  $R_H = R_S + V_{\text{ds}}/I_{\text{ds}} = R_S + 100 \Omega$ . (2) Cascade Pre-Amp and Post-Amp to form Inv-Amp, and input G is still grounded. Adjust  $R_p$  and  $R_{t1}$  to realize the DC output voltage  $V_{\text{om}}$  of Inv-Amp to 0 and HEMT still at the ideal operating point. (3) Connect output O and input G of Inv-Amp with the feedback network and disconnect input G from ground, to form TIA. Input G is still not connected with the signal source circuit, so the potential of input G and output O of Inv-Amp is still 0, since the input resistance of the transistor HEMT  $R_A$  can be considered as infinity. In the feedback network,  $R_F + R_k \approx R_F = 1$

GΩ. (4) Connect the signal source circuit to TIA, to form the CryoSTM-TIA.

When  $f \rightarrow 0$ ,  $a_A \rightarrow a_{A0}$ , and  $a_{A0}$  is the DC voltage gain of Inv-Amp.  $|a_{A0}|_{\text{dB}} \approx (g_m R_f / g_d R_H)_{\text{dB}} \approx 94.5 \text{ dB}$ , which is consistent with the simulation result  $|a_{A0}|_{\text{dB}} = 92 \text{ dB}$  shown in Fig.2. As the DC bias  $V_i$  is applied by BMS, the DC resistance of TJ is  $R$ , and the potential at input G is  $V_G$ , and the output voltage of the CryoSTM-TIA is  $V_o$ . Obviously,  $a_{A0} V_G = V_o$ , and  $(V_i - V_G)/R = (V_G - V_o)/R_F$ . The DC bias on TJ is  $V = V_i - V_G$ , and the DC tunneling current  $I = (V_i - V_G)/R$ .  $I_s$  as an approximate value of  $I$  is

$$I_s = -V_o/R_F. \quad (4.1)$$

And, the relative error is obtained as

$$Er = |I_s - I|/|I| = 1/(1 - a_{A0}).$$

As  $|a_{A0}|_{\text{dB}} \approx 92 \text{ dB}$ ,  $Er < 30 \text{ ppm}$ , consistent with the simulation results [28]. Since  $a_{A0} V_G = V_o$ , the DC bias on TJ is

$$V = V_i - V_o/a_{A0}. \quad (4.2)$$

By Eq.(4.1),  $V_o = -R_F I_s \approx -R_F I = -R_F V/R$ . By Eq.(4.2),  $V_i \approx V - R_F V/(R a_{A0})$ . As the minimum of  $R_J$  is not less than  $1 \text{ M}\Omega$ ,  $R \geq 1 \text{ M}\Omega$ , so  $|R_F/(R a_{A0})| \leq 1/40$ . Thus,  $V \approx V_i$ . With the measured  $V_o$ ,  $I \approx I_s$  and  $V \approx V_i$  can be obtained. Therefore, the scanning tunneling current spectra  $I = I(V)$  ( $V \in [V_L, V_H]$ ) can be obtained, where  $V_L$  and  $V_H$  are the lower limit and upper limit voltages for the measurements respectively.

The drift of  $V_{\text{om}}$  can be considered as the amplification of the drift of the Inv-Amp input offset voltage  $V_{\text{OS}}$ , where  $V_{\text{om}} = a_{A0} V_{\text{OS}}$ . For TIA, the output drift voltage is approximate to  $V_{\text{OS}}$ . The estimated drift of  $|V_{\text{OS}}|$  is less than  $17 \mu\text{V}/^\circ\text{C}$  [29]. The power of the power supply of Pre-Amp is less than  $40 \text{ mW}$ . The temperature control system based on the TEC devices [30] can be used to control the temperature fluctuations of the power supply and those of Rear-OPA within  $0.01^\circ\text{C}$ , so the fluctuations of  $V_{\text{OS}}$  within  $170 \text{ nV}$  is guaranteed, i.e. the TIA output fluctuations within  $170 \text{ nV}$ .

In order to verify the correctness of the above design methods for TIA, we do the following work shown in Ref.[31]. The N-Channel JFET (SST4393-T1) is chosen to replace CNRS-HEMT, and TIA is designed and fabricated with the same circuit design method and the same circuit topology. SST4393-T1 can work at  $77 \text{ K}$ . We measured the electrical performances and noise performances of the JFET-based TIA at  $77 \text{ K}$  [31]. The experimental results are basically consistent with the calculated results and simulated results, which verify the design methods for TIA in this work.

## 5 Applications for the proposed CryoSTM-TIA in spectra measurements

For most applications, the modulus of the transimpedance gain of the CryoSTM-TIA  $|A_i(f)|$  should be measured firstly.  $A_i(f)$  is expressed as Eq.(2.7). Since  $|a_A(f)|_{\text{dB}} > 90 \text{ dB}$  in  $[1 \text{ kHz}, 300 \text{ kHz}]$  as shown in Fig.2, when  $R_J \geq 10^{-3} R_F$ ,  $|A_i(f)|$  in  $[1 \text{ kHz}, 300 \text{ kHz}]$  can be approximately expressed as

$$|A_i(f)| = R_F / |1 - j2\pi f R_F (C_A + C_I) / a_A(f)|. \quad (5.1)$$

How to measure it has been described in Ref.[3].

### 5.1 Measurements of scanning tunneling differential conductance spectra by the proposed CryoSTM-TIA

The differential conductance of TJ  $G_J = 1/R_J$  is the function of the voltage  $V$  applied to TJ. As the frequency  $f$  of the modulated signal voltage  $\dot{V}_i$  provided by BMS is low enough, such as  $f < 1$  kHz, by Eq.(2.6),

$$A_v \approx -\frac{R_F}{R_J(V)} \cdot \frac{1}{1 - \frac{R_F}{a_A(f)R_J(V)}}.$$

Therefore,  $R_J(V) \approx [-1/A_v + 1/a_A(f)] R_F$ . When the measured  $|A_v| \leq 1000$ ,  $R_J(V) \approx R_F/|A_v|$ , since  $|a_A(f)|_{\text{dB}} \geq 85$  dB in  $f \leq 300$  kHz as shown in Fig.2. With the measured  $|A_v| = |\dot{V}_o|/|\dot{V}_i|$ , the differential conductance spectra  $G_J(V) = 1/R_J(V)$  ( $V \in [V_L, V_H]$ ) can be obtained.

Increasing the frequency  $f$  of the modulated signal can speed up the scanning tunneling differential conductance spectra measurements. In  $[1 \text{ kHz}, 300 \text{ kHz}]$ , as  $R_J \geq 1 \text{ M}\Omega$ , by Eq.(2.6),

$$|A_v(f)| \approx \frac{1}{|Z_J(f)|} \cdot \frac{R_F}{|1 - j2\pi f R_F(C_A + C_1)/a_A(f)|}.$$

Therefore,  $1/|Z_J(f)| \approx |A_v(f)|/|A_i(f)|$ , where  $|A_i(f)|$  is shown by Eq.(5.1). And,  $|A_v(f)|$  and  $|A_i(f)|$  can be measured.  $1/|Z_J(f)| = \sqrt{1/R_J^2 + (2\pi f C_J)^2}$  can be obtained. Selecting two different frequencies  $f_1$  and  $f_2$  in  $[1 \text{ kHz}, 300 \text{ kHz}]$ ,  $|Z_J(f_1)|$  and  $|Z_J(f_2)|$  are obtained.  $R_J$  and  $C_J$  can be solved out from the measured  $|Z_J(f_1)|$  and  $|Z_J(f_2)|$ .

Since the inherent noise of the CryoSTM-TIA is very small, the amplitude of the modulated signal voltage  $\dot{V}_i$  can be very small, so that the energy resolution for STS is much improved.

### 5.2 Measurements of scanning tunneling shot noise spectra by the proposed CryoSTM-TIA

The measurement method for the tunneling shot noise spectra by the proposed CryoSTM-TIA is basically the same as that introduced by Ref.[3], and it is only briefly described here.

Before approaching the tip to the sample in the CryoSTM,  $R_J$  can be considered as infinity and  $C_J$  as 0. In this case, the output noise voltage PSD of the CryoSTM-TIA  $S_{\text{su}}(f)$  can be measured, and the equivalent input noise current PSD  $\overline{i_i^2}(f)$  is

$$\overline{i_i^2}(f) = S_{\text{su}}(f)/|A_i(f)|^2, \quad (5.2)$$

where  $|A_i(f)|$  is obtained by Eq.(5.1).

To measure the scanning tunneling shot noise spectra (STSNS) of a quantum system by the CryoSTM-TIA, the distance between the tip and sample is adjusted, and the interval  $[V_L, V_H]$  is selected, so that the shot noise measurements at  $V \in D_V = \{V | V_L \leq V \leq V_H, G_J(V) < 1 \mu\text{S}\}$  are needed to study the physical properties of the quantum system [3]. In  $D_V$ , the output noise voltage PSD  $S_{\text{sum}}(f, V)$  can be measured. The tunneling noise current PSD is denoted as  $S_I(f, V)$ . The equivalent input noise current PSD of the

CryoSTM-TIA is the function of  $R_J$ , so it is the function of  $V$  and denoted as  $\overline{i_{\text{in}}^2}(f, V)$ . For  $S_{\text{sum}}(f, V)$ ,

$$S_{\text{sum}}(f, V) = \left[ S_I(f, V) + \overline{i_{\text{in}}^2}(f, V) \right] \cdot |A_i(f)|^2. \quad (5.3)$$

With Eq.(5.2) and (5.3), it is obtained that

$$S_I(f, V) = \frac{S_{\text{sum}}(f, V) - S_{\text{su}}(f)}{|A_i(f)|^2} - \delta(f, V),$$

where  $\delta(f, V) = \overline{i_{\text{in}}^2}(f, V) - \overline{i_i^2}(f)$ . From Eq.(3.12),

$$\overline{i_i^2}(f) = \overline{i_A^2} + \frac{4k_B T}{R_F} + \frac{\overline{e_A^2}}{R_F^2} + (2\pi f)^2 \left( C_I^2 \overline{e_A^2} + 2C_A C_I \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{\text{vP}}^2} \right).$$

And,  $\overline{i_{\text{in}}^2}(f, V)$  is composed by the four parts as shown in Eq.(3.12). According to Table 2,  $|\delta(f, V)|$  is smaller than  $0.3 \text{ (fA)}^2/\text{Hz}$  in  $[10 \text{ kHz}, 100 \text{ kHz}]$  and  $0.1 \text{ (fA)}^2/\text{Hz}$  in  $[100 \text{ kHz}, 200 \text{ kHz}]$ .  $\delta(f, V)$  can be neglected compared with  $S_I(f, V)$ , so long as the minimum of  $G_J(V)$  ( $V \in D_V$ ) is not too small. Therefore,  $S_I(f, V)$  can be obtained as

$$S_I(f, V) \approx \frac{S_{\text{sum}}(f, V) - S_{\text{su}}(f)}{|A_i(f)|^2},$$

by the measured  $S_{\text{sum}}(f, V)$ ,  $S_{\text{su}}(f)$ , and  $|A_i(f)|$ . And then, the SNTNS  $S_{\text{Is}}(I) = 2Fe|I|$  can be extracted from  $S_I(f, V)$ . Here,  $I = I(V)$  ( $V \in D_V$ ), and  $I$  is the DC tunneling current as the bias  $V$  is applied.

Compared with the CryoSTM-TIA in Ref.[3], the CryoSTM-TIA proposed in this work has the same transimpedance gain, the bandwidth is above 200 kHz, and its inherent noise is much lower. The inherent noise of the CryoTM-TIA in this work is only  $5.3 \text{ (fA)}^2/\text{Hz}$  at 100 kHz and its  $\delta(f, V) < 0.1 \text{ (fA)}^2/\text{Hz}$  at 100 kHz, while that of the apparatus in Ref.[3] is  $21 \text{ (fA)}^2/\text{Hz}$  at 100 kHz and  $\delta(f, V) < 0.28 \text{ (fA)}^2/\text{Hz}$  at 100 kHz. Therefore, as investigating novel quantum states of various quantum systems, the measurements performed with the apparatus proposed in this work is more accurate.

For example, as investigating the existence of MBS in a magnetic flux vortex of the iron superconductor in CryoSTM [4], the tunnel junction resistance must be large enough, since the occurrence of incoherent Andreev reflection can be ruled out by weak tunnel coupling conditions [32]. In Ref.[4], the tunneling current  $I$  is quite low (see Fig.3(a) in Ref.[4] and Figs2(a) and (b) in its supplemental file). As the tunnel junction bias  $V$  is 0.3 mV,  $I$  is only tens of pA, and the corresponding shot noise may only be only a few  $\text{(fA)}^2/\text{Hz}$ . For the shot noise measurements in the system in Ref.[4], it is obvious that the CryoSTM-TIA proposed in this work is much more effective and accurate than that in Ref.[3].

## 6 Conclusion

In this work, a design of transimpedance amplifier (TIA) for cryogenic scanning tunneling microscope (CryoSTM) is presented. TIA connected with the tip-sample component in CryoSTM is called as CryoSTM-TIA. The CryoSTM-TIA in this work has transimpedance

gain of  $1\text{ G}\Omega$  and bandwidth more than 200 kHz, and its equivalent input noise current PSD is only  $5.3\text{ (fA)}^2/\text{Hz}$  at 100 kHz. In this CryoSTM-TIA, a single CNRS-HEMT Pre-Amp is instead of the differential Pre-Amp consisting of a pair of CNRS-HEMTs in Ref.[3]. The difficulty of matching the identical HEMTs is avoided. And, due to the reduction of a noisy HEMT, the apparatus inherent noise is only 1/4 of that in Ref.[3]. Furthermore, the inherent noise of the single HEMT in the circuit can be in-situ reduced by “bias-cooling method”. With this apparatus, the fast high-energy-resolution scanning tunneling spectra measurements can be performed and the very low tunneling shot noise of quantum systems can be measured at the atomic scale. This apparatus can be applied to investigate novel physical properties of various quantum systems, such as detecting the existence of Majorana bound states in the topological quantum systems.

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## Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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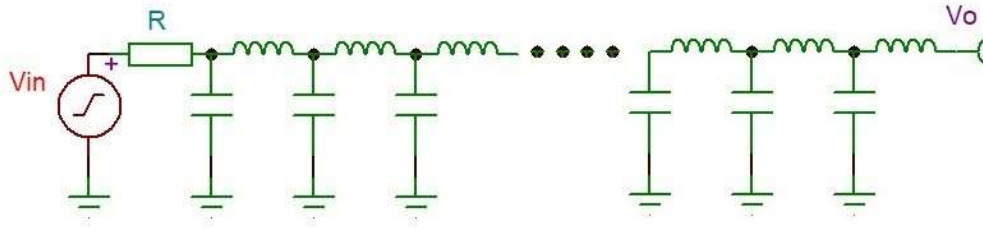
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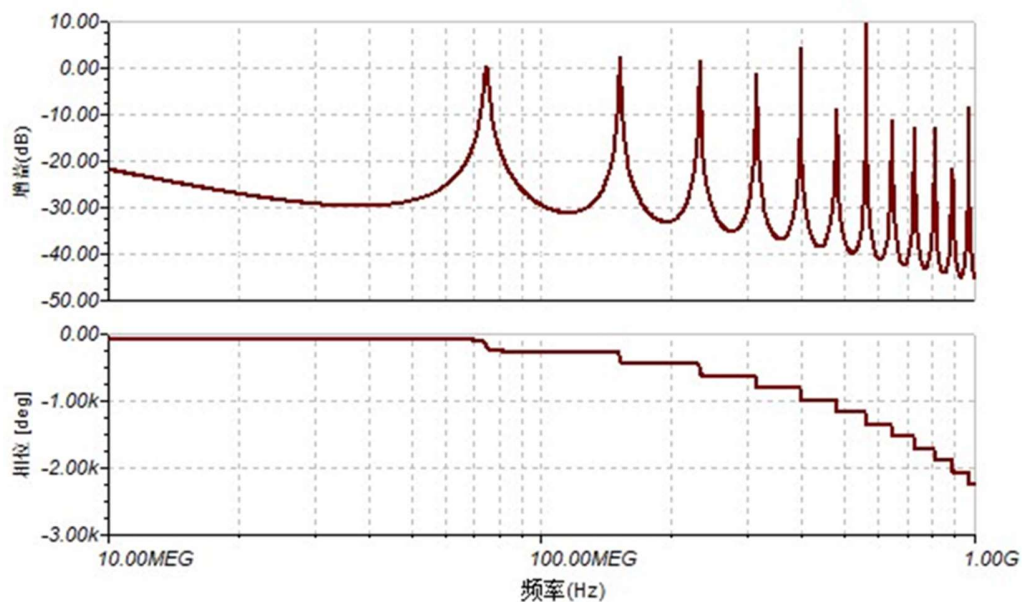
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## Supplemental file 1: Voltage gain peaks for cables

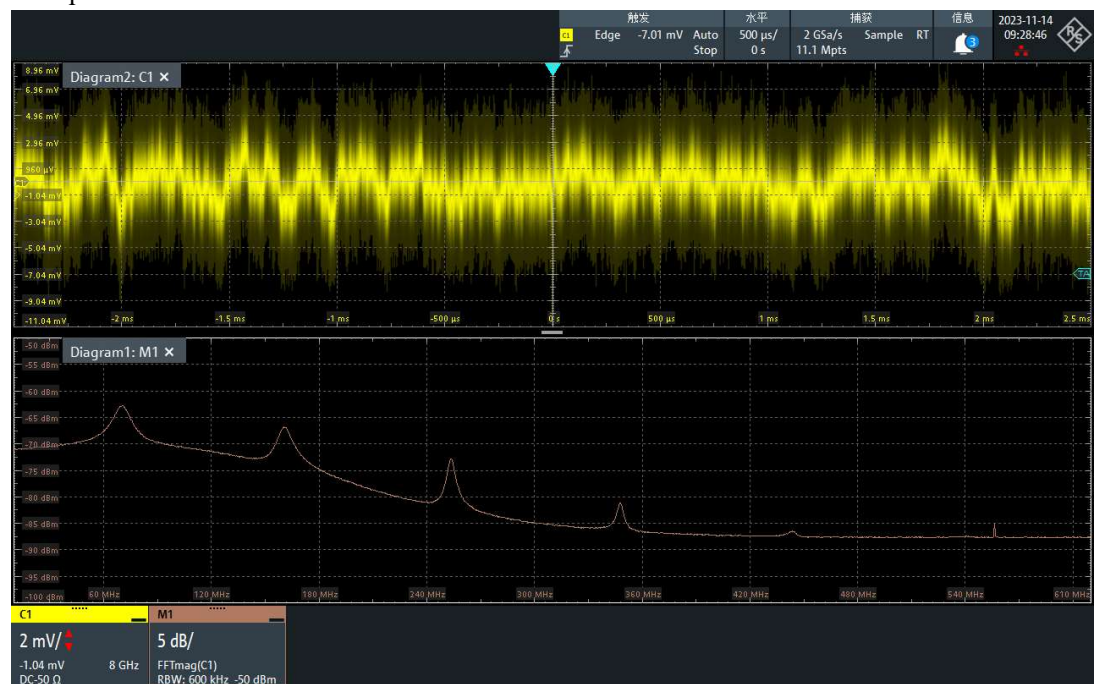


**Figure s1-1** The circuit scheme for measuring the voltage gain peaks for cables.

A 1 meter cable with characteristic impedance of  $50\ \Omega$  has a distributed capacitance of  $100\ \text{pF}$  and a distributed inductance of  $250\ \text{nH}$ , which is shown as Fig. s1-1. In Fig. s1-1,  $R=1.5\ \text{k}\Omega$ , the gain is  $V_o/V_{in}$ . The simulation results show its distributed LC structure results in several resonant gain peaks in  $[80\ \text{MHz}, 1\ \text{GHz}]$  shown as Fig. s1-2. As the input signal  $V_{in}$  is the thermal noise of  $R$  ( $1.5\ \text{k}\Omega$ ) at  $300\ \text{K}$ , we amplify  $V_o$  with Amplifier SA-220F5 (gain=200,  $f_h=200\ \text{MHz}$ ), and then the gain peaks for the cable are measured with an oscilloscope. Fig. s1-3 show the measured gain peaks for cable.

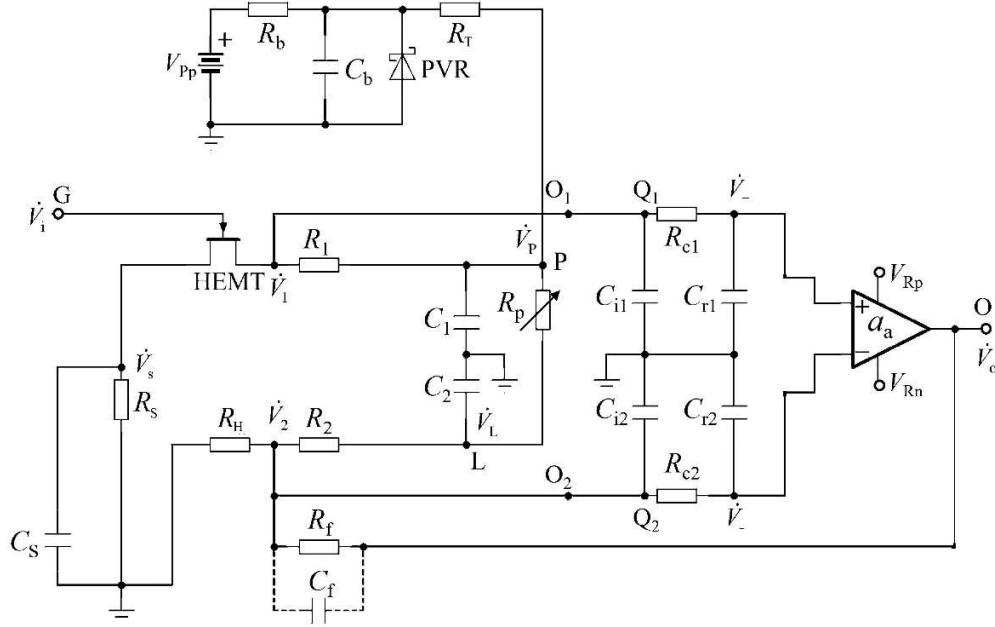


**Figure s1-2** The simulation results of the gain peaks for a 1 meter cable with a distributed capacitance of 100 pF and a distributed inductance of 250 nH.



**Figure s1-3** The input signal  $V_{in}$  is the thermal noise of  $R$  ( $1.5\text{ k}\Omega$ ) at  $300\text{ K}$ . The measured results of the gain peaks for a 1 meter cable with a distributed capacitance of 100 pF and a distributed inductance of 250 nH.

## Supplemental file 2: Voltage gain of Inv-Amp



**Figure s2-1** Inv-Amp circuit with all components for Eqs.(s2.1-s2.8), and their parameters are shown in Table 1 in Article.

With the nodal analysis method, Inv-Amp voltage gain  $a_A(f)$  is calculated by the following equations. All components for Eqs.(s2.1-s2.9) are shown in Fig.s2-1, and their parameters are shown in Table 1 in Article.

$$(\dot{V}_o - \dot{V}_2)/R_f = (\dot{V}_2 - \dot{V}_L)/R_2 + (\dot{V}_2 - \dot{V}_-)/R_{c2} + \dot{V}_2/R_H + j\omega C_{i2}\dot{V}_2, \quad (s2.1)$$

$$j\omega C_{gd}(\dot{V}_i - \dot{V}_1) = g_m(\dot{V}_i - \dot{V}_s) + g_d(\dot{V}_1 - \dot{V}_s) + (\dot{V}_1 - \dot{V}_p)/R_1 + (\dot{V}_1 - \dot{V}_+)/R_{c1} + j\omega C_i\dot{V}_2, \quad (s2.2)$$

$$(\dot{V}_1 - \dot{V}_p)/R_1 + (\dot{V}_L - \dot{V}_p)/R_p = \dot{V}_p/R_T + j\omega C_1\dot{V}_{tp}, \quad (s2.3)$$

$$(\dot{V}_2 - \dot{V}_L)/R_2 = (\dot{V}_L - \dot{V}_p)/R_p + j\omega C_2\dot{V}_L, \quad (s2.4)$$

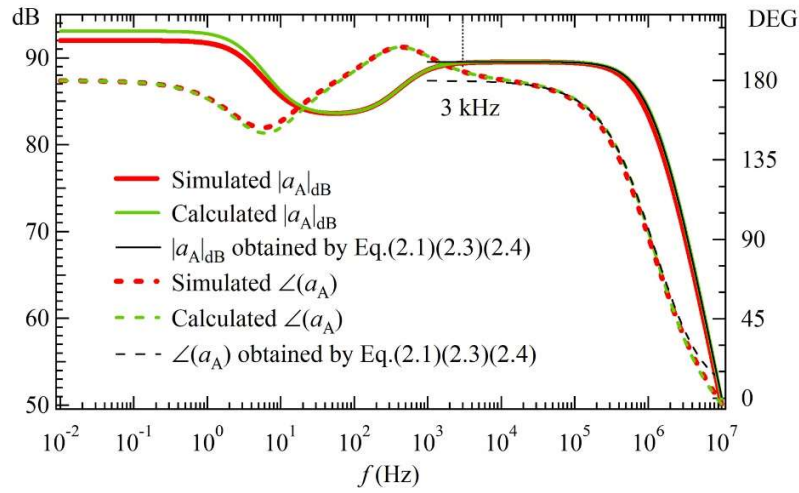
$$g_m(\dot{V}_i - \dot{V}_s) + g_d(\dot{V}_1 - \dot{V}_s) = \dot{V}_s/R_s + j\omega C_s\dot{V}_s + j\omega C_{gs}(\dot{V}_s - \dot{V}_i), \quad (s2.5)$$

$$\dot{V}_o = a_a(\dot{V}_+ - \dot{V}_-), \quad (s2.6)$$

$$(\dot{V}_2 - \dot{V}_-) / R_{c2} = +j\omega C_{r2} \dot{V}_-, \quad (\text{s2.7})$$

$$(\dot{V}_1 - \dot{V}_+) / R_{c1} = +j\omega C_{r1} \dot{V}_+, \quad (\text{s2.8})$$

$$a_A = \dot{V}_o / \dot{V}_i, \quad (\text{s2.9})$$

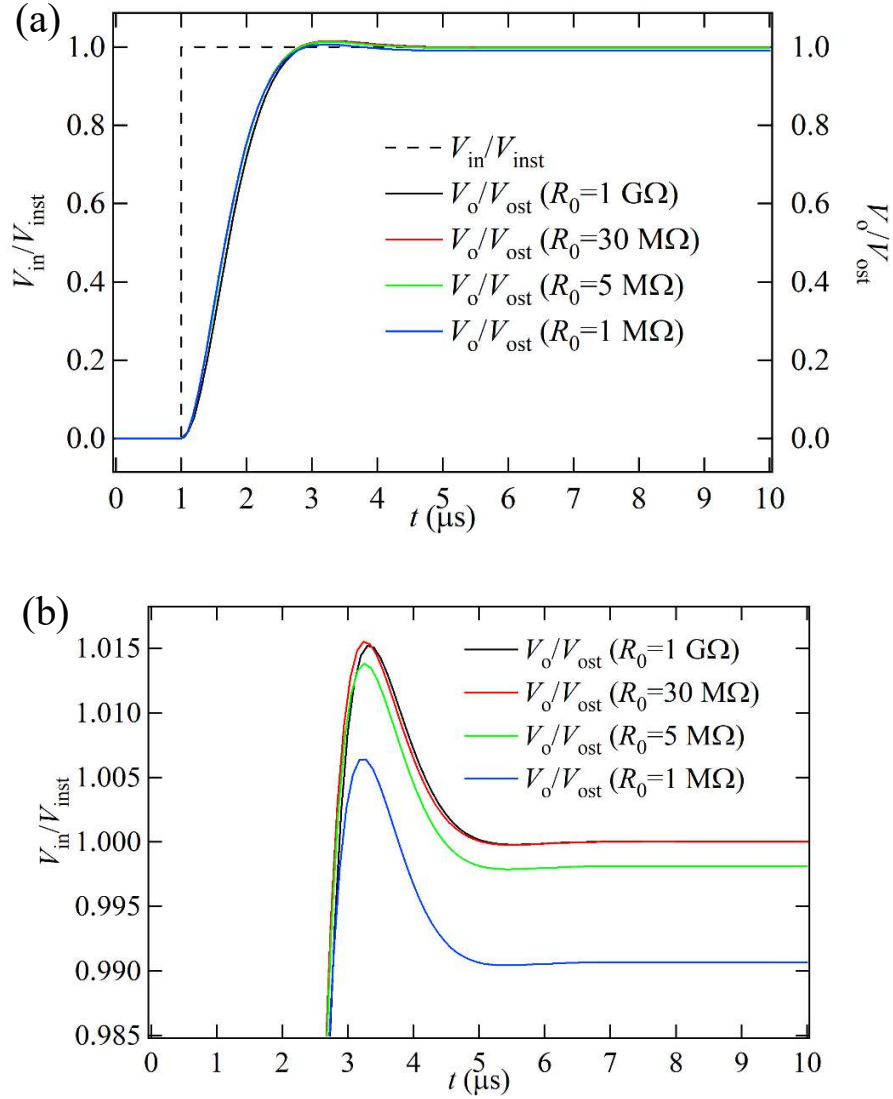


**Figure s2-2** The Inv-Amp voltage gain  $a_A(f)$ . The solid curves are the curves of  $|a_A(f)|_{\text{dB}}$ , and the dashed curves are the curves of  $\angle(a_A(f))$ . The red curves are the TINA-TI simulation results, the green curves are the calculated results with the nodal analysis method (i.e. Eqs.(s2.1-2.9)), and the black curves are the calculated results by Eqs.(2.1), (2.3), and (2.4) in Article.

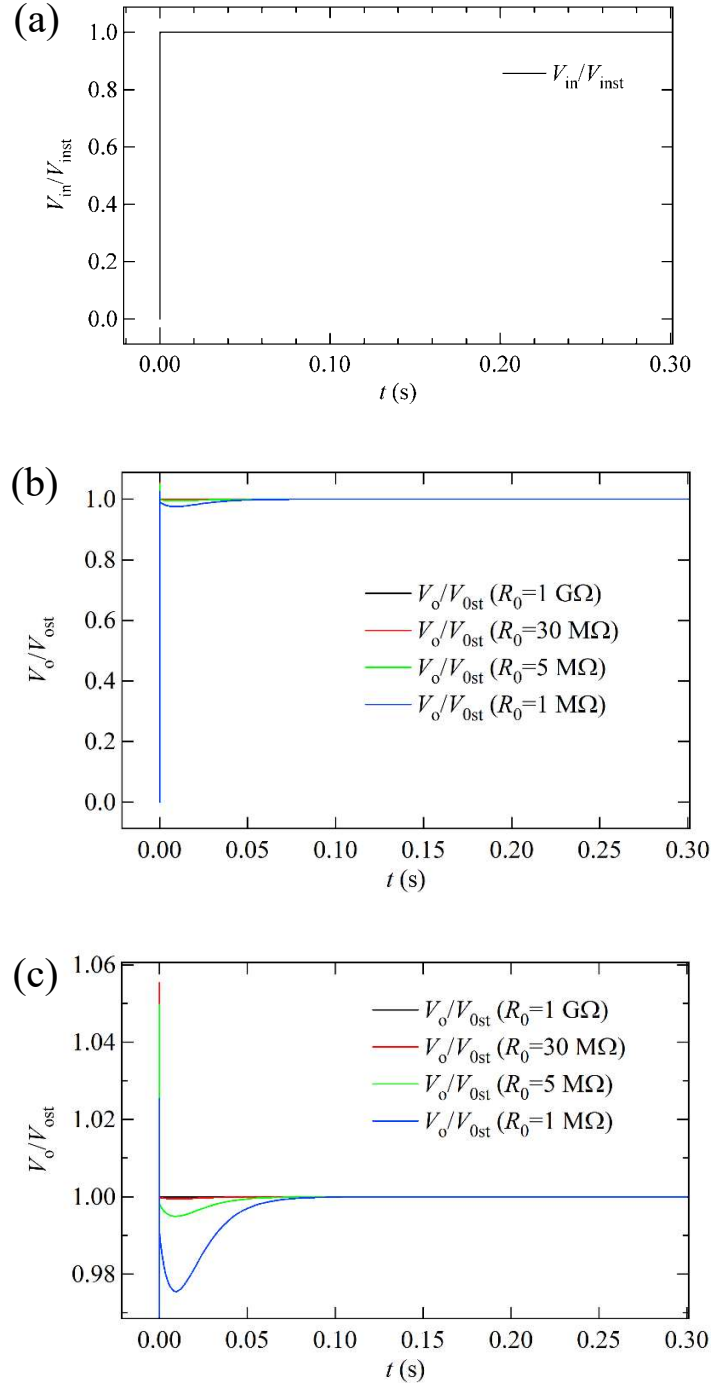
Fig. s2-2 shows the modulus of the Inv-Amp voltage gain  $|a_A(f)|_{\text{dB}}$ . The red solid curve is the TINA-TI simulation results, and the green solid curve is the calculated results with the nodal analysis method. They are identical with each other. The black solid curve is the calculated results by Eqs.(2.1), (2.3), and (2.4) in Article. In  $f \in [3 \text{ kHz}, 10 \text{ MHz}]$ , three curves are identical with one another.

Fig. s2-2 also shows the argument of the Inv-Amp voltage gain  $\angle(a_A(f))$ . The red dashed curve is the TINA-TI simulation results, and the green dashed curve is the calculated results with the nodal analysis method. They are identical with each other. The black dashed curve is the calculated results by Eqs.(2.1), (2.3), and (2.4) in Article. In  $f \in [3 \text{ kHz}, 10 \text{ MHz}]$ , three curves are consistent with one another.

### Supplemental file 3: Transient response of the proposed CryoSTM-TIA



**Figure s3-1** A resistor with a constant resistance  $R_0$  is instead of the tip-sample junction for the simulation. TINA-TI simulation results for the transient response of the CryoSTM-TIA with the different  $R_0$  for the time interval of 10 μs. The dashed curve is the step input signal  $V_i/V_{inst}$  for the different  $R_0$ . The solid curves are the output response  $V_o/V_{ost}$ . Here,  $V_{ost}$  and  $V_{inst}$  are their values respectively at 300 ms after applying the step input signal  $V_i$ , which are shown in Fig.s3-2. Transient response time  $t_r < 5$  μs. (b) is the zoom-in for the output response  $V_o/V_{ost}$  in (a).



**Figure s3-2** A resistor with a constant resistance  $R_0$  is instead of the tip-sample junction for the simulation. TINA-TI simulation results for the transient response of the CryoSTM-TIA with different  $R_0$  for the time interval of 300 ms. (a) The step input signal  $V_i/V_{inst}$ . (b) The output response  $V_o/V_{ost}$ .  $V_o/V_{ost} = 1$  in  $t \geq 100$  ms. (c) is the zoom-in figure of (b).



A resistor with a constant resistance  $R_0$  is instead of the tip-sample junction for the simulation. Fig.s3-1 shows TINA-TI simulation results for the transient response of the CryoSTM-TIA with the different  $R_0$  for the time interval of 10  $\mu\text{s}$ . The dashed curve is the step input signal  $V_i/V_{\text{inst}}$ , and the solid curves are the output response  $V_o/V_{\text{ost}}$  for the different  $R_0$ . Here,  $V_{\text{ost}}$  and  $V_{\text{inst}}$  are their values respectively at 300 ms after applying the step input signal  $V_i$ . The error is definite as  $|V_o - V_{\text{ost}}|/|V_{\text{ost}}|$ . For the CryoSTM-TIA, the time taken from adding the input step signal voltage to the output response stably within a certain error is called transient response time  $t_r$ . As shown in Fig.s3-1 and Fig.s3-2(b)&(c), with  $R_0 = 1 \text{ G}\Omega$  and  $30 \text{ M}\Omega$ , for 0.1% error,  $t_r < 5 \mu\text{s}$ . With  $R_0 = 5 \text{ M}\Omega$ , for 1% error,  $t_r < 5 \mu\text{s}$ . And, With  $R_0 = 1 \text{ M}\Omega$ , for 2.5% error,  $t_r < 5 \mu\text{s}$ .

## Supplemental file 4: Noise of the proposed CryoSTM-TIA

### S4.1 Noises of STM-TIA

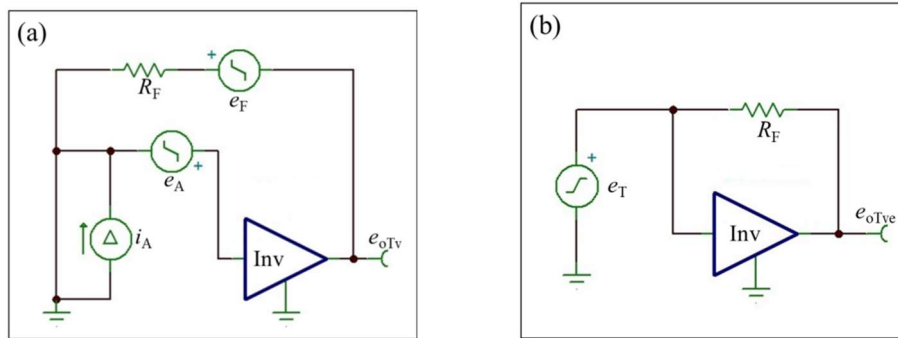
For Inv-Amp, the equivalent input noise voltage of Inv-Amp is denoted as  $e_A$  and its equivalent input noise current is  $i_A$ , and their harmonic components of frequency  $f$  are  $E_A$  and  $I_A$  respectively.

$\begin{pmatrix} E_A \\ I_A \end{pmatrix}$  can be obtained by the nodal analysis method. By Wiener-Khintchine theorem,

$\begin{pmatrix} \overline{e_A^2} & \overline{e_A i_A^*} \\ \overline{i_A e_A^*} & \overline{i_A^2} \end{pmatrix}$  can be obtained from  $\begin{pmatrix} E_A E_A^* & E_A I_A^* \\ I_A E_A^* & I_A I_A^* \end{pmatrix}$  [S4R1, S4R2]. The two matrix elements on

the main diagonal are the equivalent input noise voltage PSD of Inv-Amp  $\overline{e_A^2}$  and its equivalent input noise current PSD  $\overline{i_A^2}$ . The two matrix elements on the sub-diagonal are its equivalent input noise voltage-current PSD  $\overline{e_A i_A^*}$  and equivalent input noise current-voltage PSD  $\overline{i_A e_A^*}$ .

Inv-Amp is connected to the feedback resistor  $R_F$  to form TIA. The equivalent input noise voltage of TIA is denoted as  $e_T$  and its equivalent input noise current is  $i_T$ , and their harmonic components of  $f$  are  $E_T$  and  $I_T$  respectively. The temperature of the feedback resistance  $R_F$  is  $T$ , and its noise voltage is  $e_F$  and its harmonic component of  $f$  is  $E_F$ .

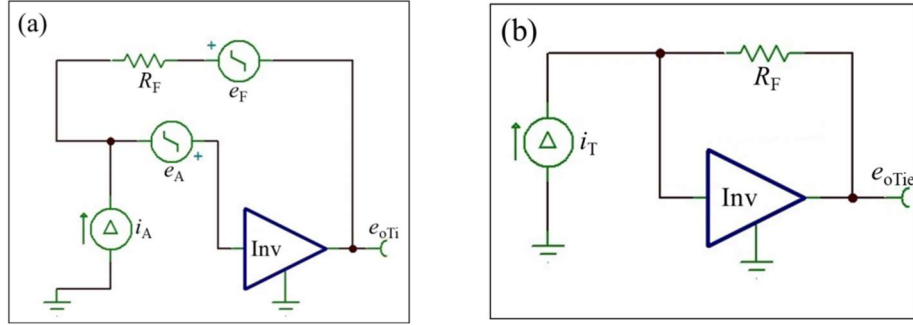


**Figure s4-1** (a) TIA circuit with the input short-circuit containing the equivalent input noise voltage of Inv-Amp  $e_A$  and its equivalent input noise current  $i_A$ , and the output noise voltage of  $e_{oTv}$ ; (b) Noiseless TIA circuit with the equivalent input noise voltage of TIA  $e_T$  as the input signal, and the output noise voltage of  $e_{oTve}$ ; the equivalency of the above two circuits means  $e_{oTv} = e_{oTve}$ .

For TIA, the circuit containing all noise sources with the input short-circuit is shown as Fig.s4-1(a), and the output noise is  $e_{oTv}$ . The noiseless circuit with the equivalent input noise voltage

of TIA  $e_T$  as the input signal is shown as Fig.s4-1(b), and the output noise is  $e_{oTve}$ . For calculating the equivalent input noise voltage of TIA, the equations are established on the equivalency of the above two circuits, i.e.  $e_{oTv} = e_{oTve}$ . Therefore, by nodal analysis method,

$$E_T = E_A .$$



**Figure s4-2** (a) TIA circuit with the input open-circuit containing the equivalent input noise current of Inv-Amp  $i_A$  and its equivalent input noise current  $i_A$ , and the output noise current of  $e_{oTi}$ ; (b) Noiseless TIA circuit with the equivalent input noise current of TIA  $i_T$  as the input signal, and the output noise voltage of  $e_{oTie}$ ; the equivalency of the above two circuits means  $e_{oTi} = e_{oTie}$ .

For TIA, the circuit containing all noise sources with the input open-circuit is shown as Fig.s4-2(a), and the output noise is  $e_{oTi}$ . The noiseless circuit with the equivalent input noise current of TIA  $i_T$  as the input signal is shown as Fig.s4-2(b), and the output noise is  $e_{oTie}$ . For calculating the equivalent input noise current of TIA, the equations are established on the equivalency of the above two circuits, i.e.  $e_{oTi} = e_{oTie}$ . Therefore, by the nodal analysis method,

$$I_T = I_A + (E_A + E_F)/R_F .$$

Hence,

$$\begin{pmatrix} E_T \\ I_T \end{pmatrix} = \begin{pmatrix} 0 \\ 1/R_F \end{pmatrix} (E_F + E_A) + \begin{pmatrix} E_A \\ I_A \end{pmatrix} .$$

From  $\begin{pmatrix} E_T E_T^* & E_T I_T^* \\ I_T E_T^* & I_T I_T^* \end{pmatrix}$ , by Wiener-Khintchine theorem,  $\begin{pmatrix} \overline{e_T^2} & \overline{e_T i_T^*} \\ \overline{i_T e_T^*} & \overline{i_T^2} \end{pmatrix}$  can be obtained. The two matrix elements on the main diagonal are the equivalent input noise voltage PSD of TIA  $\overline{e_T^2}$  and its equivalent input noise current PSD  $\overline{i_T^2}$ . The two matrix elements on the sub-diagonal are its equivalent input noise voltage-current PSD  $\overline{e_T i_T^*}$  and equivalent input noise current-voltage PSD  $\overline{i_T e_T^*}$ .

$$\overline{e_T^2} = \overline{e_A^2} \quad , \quad (s4.1)$$

$$\overline{i_T^2} = \overline{i_A^2} + 4k_B T / R_F + \overline{e_A^2} / R_F^2 \quad , \quad (s4.2)$$

$$\overline{e_{T1}^*} = \left( \overline{i_T e_T^*} \right)^* \doteq \overline{e_A i_A^*} + \overline{e_A^2} / R_F \quad . \quad (s4.3)$$

Here, the noise voltage PSD of  $R_F$  is  $\overline{e_F^2} = 4k_B T R_F$ .

TIA is connected with the signal source circuit to form a STM-TIA. The equivalent input noise current PSD of a STM-TIA  $\overline{i_{in}^2}$  can be obtained [S4R1-S4R3] by

$$\overline{i_{in}^2} = \overline{i_T^2} + \left( 1/R_J^2 + (2\pi f)^2 C_{IJ}^2 \right) \overline{e_T^2} + (1/R_J + j2\pi f C_{IJ}) \overline{e_T i_T^*} + (1/R_J - j2\pi f C_{IJ}) \overline{i_T e_T^*} \quad . \quad (s4.4)$$

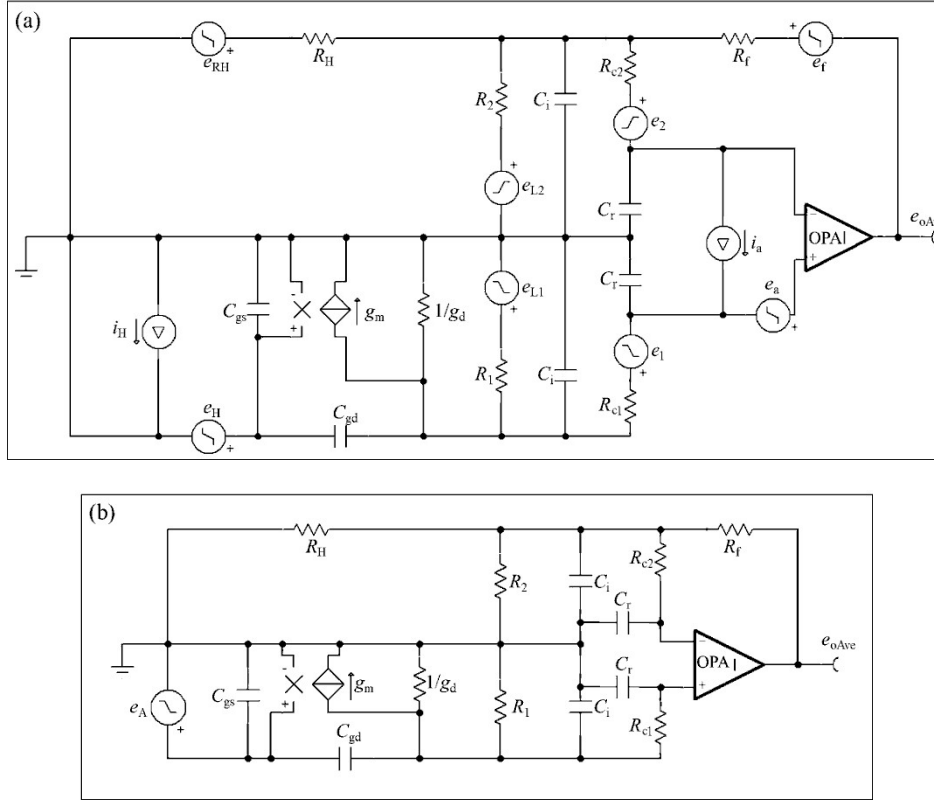
Here,  $C_{IJ} = C_I + C_J$ . Putting Eq.(s4.1), (s4.2), and (s4.3) into Eq.(s4.4),  $\overline{i_{in}^2}$  is

$$\begin{aligned} \overline{i_{in}^2} = & \overline{i_A^2} + 4k_B T / R_F + \overline{e_A^2} \left( 1/R_J^2 + 1/R_F^2 + (2\pi f)^2 C_{IJ}^2 \right) \\ & + (1/R_J + j2\pi f C_{IJ}) \left( \overline{e_A i_A^*} + \overline{e_A^2} / R_F \right) + (1/R_J - j2\pi f C_{IJ}) \left( \overline{i_A e_A^*} + \overline{e_A^2} / R_F \right) \quad . \end{aligned} \quad (s4.5)$$

## S4.2 Noises of the proposed CryoSTM-TIA

### S4.2.1 Equivalent input noise voltage and the equivalent input noise current of Inv-Amp

For Inv-Amp, the equivalent input noise voltage and equivalent input noise current of HEMT are denoted as  $e_H$  and  $i_H$  respectively, and their harmonic components of  $f$  is are denoted as  $E_H$  and  $I_H$  respectively.  $g_m$  is the transconductance of HEMT and  $g_d$  is its channel conductance. The noise voltage of the resistors  $R_H$  is denoted as  $e_{RH}$ , and the harmonic components of  $f$  are denoted as  $E_{RH}$ . The noise voltage of the resistors  $R_1$ ,  $R_2$ , and the feedback resistance  $R_f$  are denoted as  $e_{L1}$ ,  $e_{L2}$  and  $e_f$  respectively, and the harmonic components of  $f$  are denoted as  $E_{L1}$ ,  $E_{L2}$ , and  $E_f$  respectively. The noise voltage of the resistors  $R_{c1}$  and  $R_{c2}$  are denoted as  $e_1$ ,  $e_2$  and  $e_f$  respectively, and the harmonic components of  $f$  are denoted as  $E_1$ ,  $E_2$ , and  $E_f$  respectively. Here,  $R_1 = R_2 = R_L$ . All noises of  $R_H$ ,  $R_1$ ,  $R_2$ ,  $R_{c1}$ ,  $R_{c2}$ , and  $R_f$  above 1 kHz are thermal noise.  $R_d = R_L / (1/g_d)$  and  $R_{HL} = R_H // R_L$  are denoted. The equivalent input noise voltage and equivalent input noise current of Rear-OPA are denoted as  $e_a$  and  $i_a$  respectively, and the harmonic components of  $f$  are denoted as  $E_a$  and  $I_a$  respectively. These noise sources are independent of each other. For Inv-Amp consistent of Pre-Amp and Post-Amp, its equivalent input noise voltage and equivalent input noise current as  $e_A$  and  $i_A$ , the corresponding harmonic components of  $f$  are  $E_A$  and  $I_A$  respectively.



**Figure s4-3** (a) Inv-Amp equivalent differential circuit with the input short-circuit containing all noise sources, and the output noise current of  $e_{oAv}$ ; (b) Noiseless Inv-Amp circuit with the equivalent input noise voltage of Inv-Amp  $e_A$  as the input signal, and the output noise voltage of  $e_{oAve}$ ; the equivalency of the above two circuits means  $e_{oAv} = e_{oAve}$ . In (a) and (b), the triangle OPA is the Rear-OPA.

The equivalent differential circuit of Inv-Amp containing all noise sources with the input short-circuit is shown as Fig.s4-3(a), and the output noise is  $e_{oAv}$ . The noiseless circuit with the equivalent input noise voltage of Inv-Amp  $e_A$  as the input signal is shown as Fig.s4-3(b), and the output noise is  $e_{oAve}$ . For calculating the equivalent input noise voltage of Inv-Amp, the equations are established on  $e_{oAv} = e_{oAve}$ . Therefore, by the nodal analysis method,

$$E_A \approx E_H + E_{RH}Z_{HL}/(A_{vP1}R_H) - E_{L1}/(g_m R_L) + Z_{HL}(E_{L2}/R_L + E_f/R_f)/A_{vP1} + E_a/A_{vPj} + (E_1 - E_2)/A_{vP1} - (1/g_m + Z_{HL}/A_{vPj})I_a, \quad (s4.6)$$

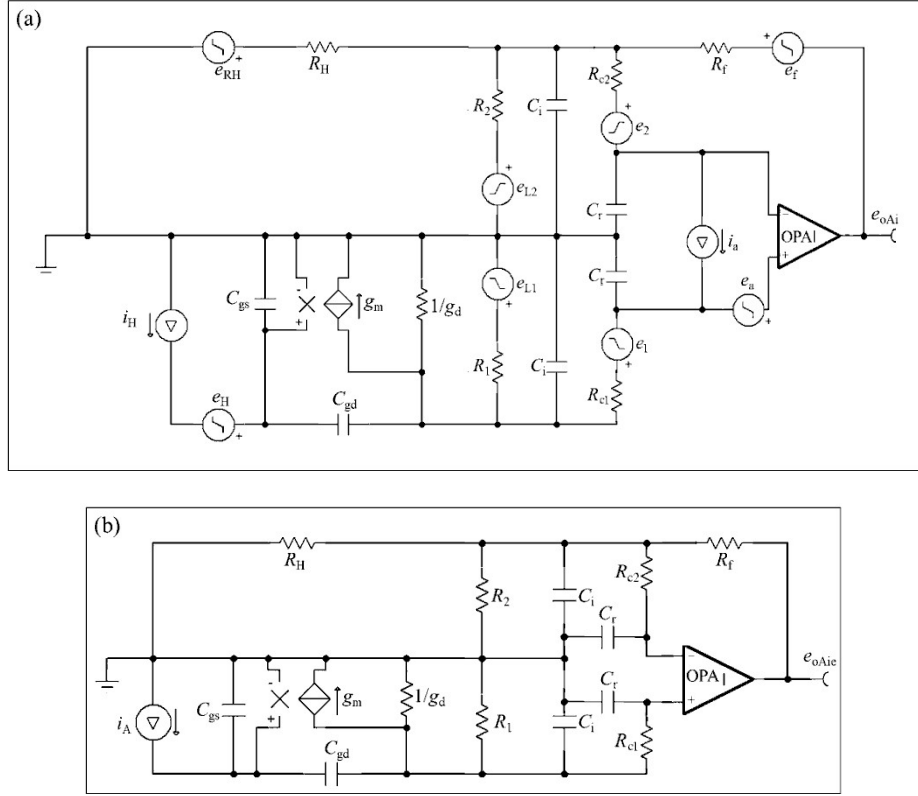
where  $A_{vP1} = g_m/[1/R_L + g_d + j(2\pi f)C_i]$ ,  $A_{vPj} = g_m/[1/R_L + g_d + j(2\pi f)C_{ir}]$ ,  $Z_{HL} = R_{HL}/[1 + j(2\pi f)R_{HL}C_{ir}]$ , and  $C_{ir} = C_i + C_r$ .

The equivalent differential circuit of Inv-Amp containing all noise sources with the input open-circuit is shown as Fig.s4-4(a), and the output noise is  $e_{oAi}$ . The noiseless circuit with the equivalent input noise current of Inv-Amp  $i_A$  as the input signal is shown as Fig.s4-4(b), and the

output noise is  $e_{oAi}$ . For calculating the equivalent input noise current of Inv-Amp, the equations are established on  $e_{oAi} = e_{oAie}$ . Therefore, by the nodal analysis method,

$$I_A \approx I_H + j(2\pi f)C_{A1}E_{RH}Z_{HL}/(A_{vP1}R_H) - j(2\pi f)C_{sd}E_{L1}/(g_m R_L) + j(2\pi f)C_{A1}Z_{HL}(E_{L2}/R_L + E_f/R_f)/A_{vP1} + j(2\pi f)(E_1 - E_2)/A_{vP1} - j(2\pi f)C_{Aj}E_a/A_{vPj} - j(2\pi f)(C_{sd}/g_m + C_{Aj}Z_{HL}/A_{vPj})I_a, \quad (s4.7)$$

where  $C_{sd} = C_{gs} + C_{gd}$ ,  $C_{A1} = C_{gs} + C_{gd}(1 + A_{vP1})$ , and  $C_{Aj} = C_{gs} + C_{gd}(1 + A_{vPj})$ .



**Figure s4-4** (a) Inv-Amp equivalent differential circuit with the input open-circuit containing all noise sources, and the output noise voltage of  $e_{oAi}$ ; (b) Noiseless Inv-Amp circuit with the equivalent input noise current of the Inv-Amp  $i_A$  as the input signal, and the output noise voltage of  $e_{oAie}$ ; the equivalency of the above two circuits means  $e_{oAi} = e_{oAie}$ . In (a) and (b), the triangle OPA is Rear-OPA.

For the measured frequency of  $f_m < 300$  kHz,  $2\pi f C_i < 0.3$  mS with  $C_i = 150$  pF and  $2\pi f C_r < 0.1$  mS with  $C_r = 50$  pF, but  $1/R_d = g_d + 1/R_L = 2$  mS and  $1/R_{HL} = 1/R_H + 1/R_L = 6$  mS, so  $A_{vP1} = g_m/[1/R_L + g_d + j(2\pi f)C_i]$  and  $A_{vPj} = g_m/[1/R_L + g_d + j(2\pi f)C_{ir}]$  are approximately simplified to  $-A_{vP} = g_m/(1/R_L + g_d) = g_m R_d$ ,  $Z_{HL}$  to  $R_{HL}$ , and  $C_{Aj}$  to  $C_A$ . Thus,

$$\begin{pmatrix} E_A \\ I_A \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} I_H + \begin{pmatrix} 1 \\ 0 \end{pmatrix} E_H - \begin{pmatrix} 1 \\ j(2\pi f)C_A \end{pmatrix} \frac{R_{HL}E_{RH}}{A_{vP}R_H} - \begin{pmatrix} 1 \\ j(2\pi f)C_{sd} \end{pmatrix} \frac{E_{L1}}{g_m R_L} - \begin{pmatrix} 1 \\ j(2\pi f)C_A \end{pmatrix} \frac{R_{HL}E_{L2}}{A_{vP}R_L} - \begin{pmatrix} 1 \\ j(2\pi f)C_A \end{pmatrix} \frac{R_{HL}E_f}{A_{vP}R_f} - \begin{pmatrix} 1 \\ j(2\pi f)C_A \end{pmatrix} \frac{E_1 - E_2 - E_a}{A_{vP}} - \begin{pmatrix} 1 + R_{HL}/R_d \\ j(2\pi f)(C_{sd} + C_A R_{HL}/R_d) \end{pmatrix} \frac{I_a}{g_m} \quad (s4.8)$$

By Wiener-Khintchine theorem, ignoring the small quantities, such as the thermal noise of  $R_L$ ,

$R_2$ , and  $R_f$ ,

$$\overline{e_A^2} \doteq \overline{e_H^2} + \left[ \left( R_{HL}^2 / R_H^2 \right) \overline{e_{RH}^2} + \left( \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) \right] / A_{vp}^2 + (1 + R_{HL} / R_d)^2 \overline{i_a^2} / g_m^2, \quad (s4.9)$$

$$\overline{i_A^2} \doteq \overline{i_H^2} + (2\pi f)^2 C_A^2 \frac{R_{HL}^2}{R_H^2} \frac{\overline{e_{RH}^2}}{A_{vp}^2} + (2\pi f)^2 C_A^2 \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{vp}^2} + (2\pi f)^2 \left( C_{sd} + \frac{R_{HL}}{R_d} C_A \right)^2 \frac{\overline{i_a^2}}{g_m^2}, \quad (s4.10)$$

$$\overline{e_A i_A^*} = \left( \overline{i_A e_A^*} \right)^* \doteq -j(2\pi f) \left[ C_A \left( \frac{R_{HL}^2}{R_H^2} \frac{\overline{e_{RH}^2}}{A_{vp}^2} + \frac{\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}}{A_{vp}^2} \right) + \left( C_{sd} + \frac{R_{HL}}{R_d} C_A \right) \left( 1 + \frac{R_{HL}}{R_d} \right) \frac{\overline{i_a^2}}{g_m^2} \right]. \quad (s4.11)$$

Here,  $\overline{e_H^2}$  is the equivalent input noise voltage PSD of the CNRS-HEMT and  $\overline{i_H^2}$  is their equivalent input noise current PSD.  $\overline{e_a^2}$  is the equivalent input noise voltage PSD of the Rear-OPA and  $\overline{i_a^2}$  is its equivalent input noise current PSD.  $\overline{e_1^2}$ ,  $\overline{e_2^2}$ , and  $\overline{e_{RH}^2}$  are the thermal noise voltage PSD of  $R_{c1}$ ,  $R_{c2}$ , and  $R_{RH}$  respectively.

$\overline{e_1^2} = \overline{e_2^2} = 4k_B T_R R_c = 1.66 \text{ (nV)}^2/\text{Hz}$ , where  $T_R$  is 300 K.  $\overline{e_a^2} = 2.25 \text{ (nV)}^2/\text{Hz}$  and  $\overline{i_a^2} = 4 \text{ (pA)}^2/\text{Hz}$  in  $f \geq 10 \text{ kHz}$  [S4R4]. In Eq.(s4.9)-(s4.11),  $\left( R_{HL}^2 / R_H^2 \right) \overline{e_{RH}^2}$  is two orders of magnitude smaller than  $\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}$ .  $(1 + R_{HL} / R_d)^2 \overline{i_a^2} / g_m^2$  is one order of magnitude smaller than  $\overline{e_H^2}$  in Eq.(s4.9).  $(C_{sd} + C_A R_{HL} / R_d)^2 \overline{i_a^2} / g_m^2$  is one order of magnitude smaller than  $C_A^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2$  in Eq.(s4.10).  $(C_{sd} + C_A R_{HL} / R_d)(1 + R_{HL} / R_d) \overline{i_a^2} / g_m^2$  is one order of magnitude smaller than  $C_A (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2$  in Eq.(s4.11). Further ignoring the small quantities in Eq.(s4.9)-(s4.11),

$$\overline{e_A^2} \doteq \overline{e_H^2} + \left( \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) / A_{vp}^2, \quad (s4.12)$$

$$\overline{i_A^2} \doteq \overline{i_H^2} + (2\pi f)^2 C_A^2 \left( \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) / A_{vp}^2, \quad (s4.13)$$

$$\overline{e_A i_A^*} = \left( \overline{i_A e_A^*} \right)^* \doteq -j(2\pi f) C_A \left( \overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2} \right) / A_{vp}^2. \quad (s4.14)$$

#### S4.2.2 Equivalent input noise voltage and the equivalent input noise current of TIA

For TIA, putting Eq. (s4.12) into Eq. (s4.1), putting Eqs. (s4.12) and (s4.13) into Eq. (s4.2), and putting Eqs. (s4.12) and (s4.14) into Eq. (s4.3), its equivalent input noise voltage PSD  $\overline{e_T^2}$  and its equivalent input noise current PSD  $\overline{i_T^2}$ , its equivalent input noise voltage-current PSD  $\overline{e_T i_T^*}$ , and its

equivalent input noise current-voltage PSD  $\overline{i_T e_T^*}$  are obtained as

$$\overline{e_T^2} \doteq \overline{e_H^2} + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2, \quad (s4.15)$$

$$\overline{i_T^2} \doteq 4k_B T / R_F + \overline{e_H^2} / R_F^2 + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / (A_{vp}^2 R_F^2) + \overline{i_H^2} + (2\pi f)^2 C_A^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2, \quad (s4.16)$$

$$\overline{e_T i_T^*} = (\overline{i_T e_T^*})^* \doteq \overline{e_H^2} / R_F + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / (A_{vp}^2 R_F) - j(2\pi f) C_A (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2. \quad (s4.17)$$

### S4.2.3 The equivalent input noise current of the proposed CryoSTM-TIA

Putting Eq.(s4.15), (s4.16), and (s4.17) into Eq.(s4.4), the equivalent input noise current PSD of the proposed CryoSTM-TIA  $\overline{i_{in}^2}$  is obtained as

$$\overline{i_{in}^2} = \overline{i_H^2} + 4k_B T / R_F + (1/R_J + 1/R_F)^2 \left[ \overline{e_H^2} + (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2 \right] + (2\pi f)^2 \left[ C_{IJ}^2 \overline{e_H^2} + C^2 (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2 \right], \quad (s4.18)$$

where  $C_{IJ} = C_I + C_J$  and  $C = C_A + C_I + C_J$ . Eq.(s4.18) is Eq.(3.11) in Article. And,

$$\overline{i_{in}^2} = \overline{i_A^2} + 4k_B T / R_F + (1/R_J + 1/R_F)^2 \overline{e_A^2} + \overline{i_{C_{IJ}}^2}, \quad (s4.19)$$

where  $\overline{i_{C_{IJ}}^2} = (2\pi f)^2 \left[ C_{IJ}^2 \overline{e_A^2} + 2C_A C_{IJ} (\overline{e_a^2} + \overline{e_1^2} + \overline{e_2^2}) / A_{vp}^2 \right]$ . Eq.(s4.19) is Eq.(3.12) in Article.

[S4R1] A. van der Ziel, Noise in Solid State Devices and Circuits, Wiley-Inter-Science, New York, (1986).

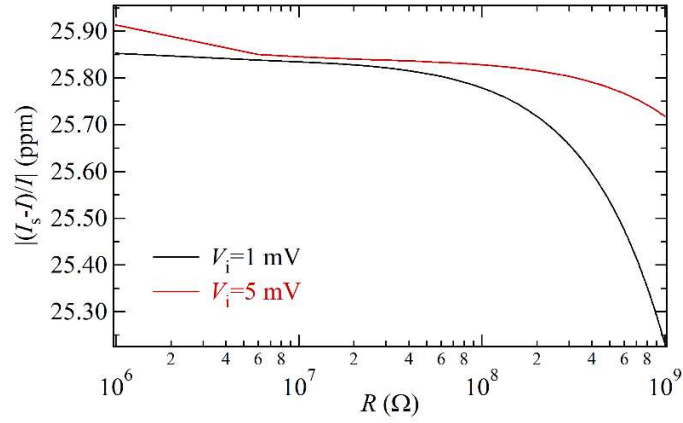
[S4R2] Y.X. Liang, Low-noise large-bandwidth transimpedance amplifier for measuring scanning tunneling shot noise spectra in cryogenic STM and its applications, Ultramicroscopy, 234 (2022) 13466.

[S4R3] Z.H. Qian, Study on noise models algorithms and matrix descriptions for integrated circuits, J. Northeast Norm. Univ. 35 (2003) 41.

[S4R4] Data sheet of THS4021 OPA, <https://www.ti.com/lit/ds/symlink/ths4021.pdf>.3.



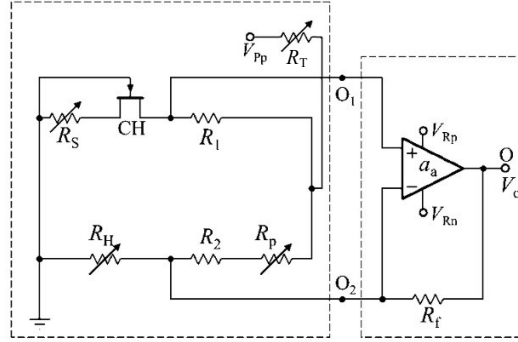
## Supplemental file 5: Estimating the DC tunneling current error for CryoSTM-TIA



**Figure s5-1** For the proposed CryoSTM-TIA,  $Er = |I_s - I|/|I|$  vs.  $R$  ( $R \in [1 \text{ M}\Omega, 1 \text{ G}\Omega]$ ) is simulated by TINA-TI with  $V_i = 1$  mV (Black curve) and  $V_i = 5$  mV (Red curve).

For the proposed CryoSTM-TIA, Fig. s5-1 shows the TINA-TI simulation results  $Er = |I_s - I|/|I|$  vs.  $R$  ( $R \in [1 \text{ M}\Omega, 1 \text{ G}\Omega]$ ) with  $V_i = 1$  mV (Black curve) and  $V_i = 5$  mV (Red curve). The simulation results show  $Er < 30$  ppm, consistent with the calculated results in Article.

## Supplemental file 6: Estimation of Inv-Amp input offset voltage



**Figure s6-1** DC circuit of the inverting amplifier.

**Table s6-1** Parameters of THS4021 [S6R1] as Rear-OPA in Post-Amp

Open loop DC voltage gain $a_{a0}$	97.5 dB
Input offset voltage drift $ v_{off} /^{\circ}\text{C}$	15 $\mu\text{V}/^{\circ}\text{C}$
Input bias current $I_{bp}, I_{bn}$	3 $\mu\text{A}$
Input bias current drift $ i_{bp} /^{\circ}\text{C},  i_{bn} /^{\circ}\text{C}$	Estimated as 100 nA/ $^{\circ}\text{C}$
CMRR	95 dB
$a_c = a_{a0}/\text{CMRR}$	2.5 dB

Pre-Amp in the left dashed box of Fig.s6-1 is made of CNRS-HEMT CH. Source of CH is grounded via a variable resistor  $R_S$ . Drain of CH is connected to  $R_1$ . A variable resistor  $R_p$  is adjustable from 0 to 10  $\Omega$ .  $R_1=R_2=R_L=1$  k $\Omega$ . Its input (Gate of CH) is grounded. Its two outputs  $O_1$  and  $O_2$  are disconnected from Post-Amp. PVR LM4050-10 is used in the power supply to provide a constant voltage of 10 V (i.e.  $V_{pp}=10$  V here) with the typical temperature coefficient (T.C.) of  $\pm 40$  ppm/ $^{\circ}\text{C}$  [S6R2]. Keep  $R_p=0$  and adjust  $R_T$ ,  $R_S$ , and  $R_H$  to realize CH at the ideal operating point ( $I_{ds}=1$  mA,  $V_{ds}=100$  mV) and the DC voltage at  $O_1$  equal to that at  $O_2$ . The gate-source voltage  $V_{gs}=-I_{ds}R_S$ . For the ideal operating point,  $V_{gs}=-50$  mV is assumed, so  $R_S=50$   $\Omega$  and  $R_H=150$   $\Omega$ .

Cascade Pre-Amp and Post-Amp to form Inv-Amp, and adjust  $R_T$  and  $R_p$  to realize CH still at the ideal operating point and the DC voltage at O to be 0.

For Inv-Amp, assuming the output voltage drift of  $v_o$  for 1 °C, the voltage drift at the output  $O_1$  is  $v_1$ , and it at  $O_2$  is  $v_2$ . The voltage drift at the output of the power supply is  $v_t$ , the voltage drift at PVR is  $v_p$ , and the voltage drift at the source of CH is  $v_s$ . By the following equations, the input offset voltage drift of Inv-Amp can be obtained.

$$(v_t - v_1)/R_L + (v_t - v_2)/R_L = (v_p - v_t)/R_T, \quad (s6.1)$$

$$(v_t - v_1)/R_L = g_d(v_1 - v_s) - g_m v_s + i_{bp}, \quad (s6.2)$$

$$(v_o - v_2)/R_f + (v_t - v_2)/R_L = v_2/R_H + i_{bn}, \quad (s6.3)$$

$$v_s/R_S = g_d(v_1 - v_s) - g_m v_s, \quad (s6.4)$$

$$a_{a0}(v_1 + v_{off} - v_2) + a_c(v_1 + v_{off} + v_2)/2 = v_o, \quad (s6.5)$$

$$v_{OS} = v_o/a_{A0}. \quad (s6.6)$$

$$a_{A0} = -g_m R_f / (g_d R_H). \quad (s6.7)$$

where,  $v_{OS}$  is the input offset voltage drift of Inv-Amp for 1 °C. From the above equations,  $v_{OS}$  and  $v_s$  can be solved out as  $v_{OS} \approx i_{bp}(1 + g_m R_S)/g_m - i_{bn} g_d R_H / g_m - v_p(1 + g_m R_S)/(2g_m R_T) - v_{off}(1 + 2g_d R_L + g_m R_S)/(2g_m R_L)$  and  $v_s \approx v_p R_S / (2R_T) - i_{bp} R_S$ .

Therefore,  $|v_p| \leq 0.4$  mV is the current drift of the power supply for 1 °C. High precision resistors with low T.C. are used in this work, so the drifts generated by the resistors can be neglected. Only considering the drifts generated by PVR and Rear-OPA,  $|v_s| < 10$  μV, and  $|v_{OS}| < 17$  μV. The power of LM4050-10 is less than 40 mW in this work, and the power of THS4021 is less than 200 mW. It is easy to control the temperature fluctuations of LM4050-10 and that of THS4021 within 0.01 °C with the temperature Control System [S6R3], so the total input voltage drift of Inv-Amp can be controlled within 170 nV.

[S6R1] Webpage of THS4021 OPA, <https://www.ti.com/product/THS4021>.

[S6R2] Data sheet of LM4050-10, <https://www.ti.com.cn/document-viewer/cn/lm4050-n/datasheet>.

[S6R3] A suitable TEC device, <https://datasheets.maximintegrated.com/en/ds/MAX1978-MAX1979.pdf>.